Lateral Epitaxial Overgrowth (From Theory to Design) Workshop

DEPARTMENT OF THE NAVY • OFFICE OF NAVAL RESEARCH

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MEETING PROGRAM & ABSTRACT BOOK

August 2-6, 1999
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Lateral Epitaxial Overgrowth Program

Sunday, 1 August: Welcoming Reception: 7:30 p.m. - 9:00 p.m.

	Speaker Name/Presentation Title
Session 1: Monday, 2 August (8:30 am - Noon) - STRUCTURAL CHARACTERIZATION/LEO GROWTH MECHANISMS, MOCVD & HVPE	
7:30 a.m. - 8:30 a.m. - Registration and Continental Breakfast	
8:30 a.m. - Welcome & Orientation - Colin Wood	
8:50 a.m. - 9:20 a.m. (Scene-setter)	**Davis, Robert -** Lateral and Pendeo-Epitaxial Growth of GaN and Related Materials on 6H-SiC(0001) and Si(111) Substrates and Their Characterization
9:20 a.m. - 9:40 a.m.	**Beaumont, Bernard -** A Two Step Process for Epitaxial Lateral Overgrowth of GaN
9:40 a.m. - 10:00 a.m.	**Kuech, Thomas -** Lateral Epitaxial Overgrowth Using Alternative Sources
10:00 a.m. - 10:20 a.m.	**Marchand, Hugues -** Electrical and Structural Properties of GaN Laterally Overgrown on GaN/Al_2O_3 and AlN/Si (111) Substrates
Break: 10:20 a.m. - 10:40 a.m.	
10:40 a.m. - 11:00 a.m.	**Zheeleva, Tsvetanka -** Lateral Epitaxial Overgrowth vs. Pendeo-Epitaxy of GaN Structures – A Finite Element Analysis
11:00 a.m. - 11:20 a.m.	**Razeghi, Manijeh** - LEO of III-Nitride on Al_2O_3 and Si Substrates
11:20 a.m. - 11:40 a.m.	**Keller, Stacia -** Maskless Dislocation Reduction in GaN Films
11:40 a.m. - 12:00 noon	**Hersee, Steve -** The Application of Nanoheteroepitaxy to the OMVPE Growth of GaN on Silicon
Lunch - 12:00 noon - 1:00 p.m. - Monday afternoon free - **Optional Tour:** Gold Panning/Gold History Tour	
Session 2: Monday PM (7:00 pm - 9:00 pm)	
6:15 p.m. - Refreshments	
6:30 p.m. - 7:00 p.m. (Scene-setter)	**Suski, Tadeusz** - Properties of Undoped and Doped (Mg, Be, Er) Bulk GaN Crystals Obtained by High Pressure Synthesis
7:00 p.m. - 7:20 p.m.	**Molnar, Richard** - ELO HVPE Growth of GaN
7:20 p.m. - 7:40 p.m.	**Kuan, T.S.** - Dislocation Mechanisms in the GaN Lateral Overgrowth by HVPE
7:40 p.m. - 8:00 p.m.	**Speck, Jim** - Dislocations and Dislocation Reduction in LEO
8:00 p.m. - 8:20 p.m.	**Liliental-Weber, Zuzanna -** Advantages and Problems of Lateral Overgrowth of GaN Layers
8:20 p.m. - 8:40 p.m.	**Usui, Akira** - Epitaxial Lateral Overgrowth by Hydride VPE
8:40 p.m. - 9:00 p.m.	**Dimitriev, Vladimir -** Mask-free Nano-size Epitaxial Lateral Overgrowth (NELOG) Technique for GaN and SiC
Tuesday a.m. 9:00 - 12:00 Noon - Boat Trip/Wildlife Tour - Buses Depart at 8:30 AM	
Lunch - 12:30 p.m. - 1:30 p.m. (at Hotel)	
Session 3: Tuesday PM 3 August (1:30 PM - 5:00 PM) MBE	
1:30 p.m. - 2:00 p.m. (Scene-setter)	**Dabiran, Amir** - Lateral MBE Growth of GaN on Patterned GaN/Sapphire
2:00 p.m. - 2:20 p.m.	**Myers, Tom -** The Influence of Active Nitrogen Species on High Temperature Limitations for GaN Growth by RF-Plasma Assisted Molecular Beam Epitaxy
2:20 p.m. - 2:40 p.m.	**Wicks, Gary** - Addressing the GaN Substrate Problem with Ammonia-based MBE
2:40 p.m. - 3:00 p.m.	**Morkoc, Hadis -** Nitride Semiconductors and MBE
Break: 3:00 p.m. - 3:20 p.m.	
3:20 p.m. - 3:40 p.m.	**Dhar, N.** - Application of LEO Technique for the ZnTe/CdTe Growth and Its Use in Enhancing Army's Capabilities in the Next Generation HgCdTe Based Infrared Focal Plane Arrays
3:40 p.m. - 4:00 p.m.	**Monemar, Bo** -Radiative Recombination in InGaN/GaN Multiple Quantum Wells
Tuesday Evening: Reception & Gold Creek Salmon Bake - Buses depart at 7:00 p.m.	

	Speaker Name/Presentation Title
Session 4: Wednesday AM 4 August (8:50 am - 12:00 noon) ELECTRICAL & OPTICAL CHARACTERISTICS	
8:30 a.m. - 9:00 a.m. - Continental Breakfast	
9:00 a.m. - 9:30 a.m. (Scene-setter)	**Freitas, Jr., Jaime** - Optical and Electronic Properties of Lateral Epitaxial Overgrown GaN Layers
9:30 a.m. - 9:50 a.m.	**DenBaars, Steven** - GaN Lateral Epitaxial Overgrowth (LEO) on Sapphire and Silicon Substrates and Recent Device Results
9:50 a.m. - 10:10 a.m.	**Dupuis, Russell** - Properties of Gallium Nitride Selective-Area and Lateral Epitaxial Overgrowth Films by MOCVD
10:10 a.m. - 10:30 a.m.	**Hiramatsu, Kazumasa** - Crystalline and Optical Properties of ELO GaN Using W Mask by MOVPE and HVPE
Break: 10:30 a.m. - 10:50 a.m.	
10:50 a.m. - 11:10 a.m.	**Khan, M. Asif** - Selective Area Epitaxial Growth of AlInGaN-GaN over Sapphire, SiC and Silicon Substrates
11:10 a.m. - 11:30 a.m.	**Long, Frederick** - Raman Microscopy of LEO GaN
11:30 a.m. - 11:50 a.m.	**Dapkus, Daniel** - Pattern Dependent LEO of GaN on Al_2O_3 and Si
Lunch - 12:00 noon - 1:00 p.m.	
Wednesday afternoon free. Optional Tour: Mendenhall Glacier Float Trip	
Session 5: Wednesday PM (7:00 pm - 9:10 pm) - DEVICES ON LEO MATERIALS	
6:45 p.m. - 7:00 p.m. - Refreshments	
7:00 p.m. - 7:30 p.m. (Scene-setter)	**Nakamura, Shuji** - Violet InGaN-MQW/GaN/AlGaN Laser Diodes Grown on LEO GaN
7:30 p.m. - 7:50 p.m.	**Jacobs, Koen** - Lateral Epitaxial Overgrowth for GaN-based LEDs
7:50 p.m. - 8:10 p.m.	**Shur, Michael** - Nitride Materials Quality as a Key to Better Device Performance
8:10 p.m. - 8:30 p.m.	**Mishra, Umesh** - Electronic Device Implications of LEO
8:30 p.m. - 8:50 p.m.	**Zolper, John** - LEO for AlGaN Electronic Devices: Do We Need It?
8:50 p.m. - 9:10 p.m.	**Babcock, Susan** - Dislocation Arrangements in Thick LEO GaN
Session 6: Thursday AM 5 August (8:30 AM - 12:00 noon) - LEO ON SI AND SIC	
8:00 a.m. - 8:30 a.m. - Continental Breakfast	
8:30 a.m. - 9:00 a.m. (Scene-setter)	**Spencer, Michael** - High Temperature Masks for the Selective and Lateral Overgrowth of SiC and AlN
9:00 a.m. - 9:20 a.m.	**Sudarshan, Tangali** - Local Epitaxy and Lateral Epitaxial Overgrowth of SiC
9:20 a.m. - 9:40 a.m.	**Edgar, James** - The Selective Epitaxy of 3C-SiC on Si and 6H-SiC Substrates
9:40 a.m. - 10:00 a.m.	**Saddow, Stephen** - Lateral Epitaxial Overgrowth of 3C-SiC on Si Substrates
Break: 10:00 a.m. - 10:20 a.m.	
10:20 a.m. - 10:40 a.m.	**Sivananthan, S. and Sporken, R.** - Investigation of the Nucleation of CdTe on Si Surfaces by TEM, XPS and RHEED
10:40 a.m. - 11:00 a.m.	**Lagnado, Isaac** - Silicon-on-Sapphire
11:00 a.m. - 11:20 a.m.	**Fergusen, Ian** - Scaling LEO to Large Area Growth
11:20 a.m. - 11:40 a.m.	**Kong, Hua-Shuang** - Recent Development in Nitride Emitters on SiC
11:40 a.m. - 12:00 noon	**Trew, Bob** - DoD Basic Research and Interests in Wide Bandgap Semiconductors
Lunch - 12:00 noon - 1:00 p.m.	
Thursday afternoon free. Optional Tour: Angler's Choice Sportsfishing	
Friday AM - 6 August - (8:30 am - 11:00 am) Wrap-up Session	

Lateral and Pendeo-epitaxial Growth of GaN and Related Materials on 6H-SiC(0001) and Si(111) Substrates and Their Characterization

Robert F. Davis, T. Gehrke, Kevin J. Linthicum, E. P. Carlson, P. Rajagopal, E. A. Preble, D. L. Nida, C.A. Zorman*, and M. Mehregany*, Department of Materials Science and Engineering, North Carolina State University, Raleigh, NC 27965, *Department of Electrical, Systems and Computer Engineering and Science, Case Western Reserve University, Cleveland, OH 44106

Conventional heteroepitaxial growth of GaN on low temperature GaN or AlN buffer layers previously deposited on Al2O3 and SiC substrates results in films containing a high dislocation density (108-1010 cm-2) due to the lattice mismatches between the buffer layer and the film and/or the buffer layer and the substrate. The objective of this research has been the significant reduction in dislocation density in GaN thin films via special methods of MOVPE growth.

Lateral epitaxial overgrowth (LEO) of GaN stripes patterned in an SiO2 mask deposited on GaN film/AlN buffer layer/6H-SiC(0001) substrates was the initial method. The mask contained 3mm and 5mm wide stripe openings, spaced parallel at 3-40mm, and oriented along < > and < > in the GaN film. The deposited material grew vertically to the top of the mask and then both laterally over the mask and vertically until coalescence. The average RMS roughness of the LEO layers was 0.25 nm. This is similar to the values of the seed GaN films. Threading dislocations, originating from the GaN/AlN buffer layer interface, propagated to the top surface of the regrown GaN layer within the window regions of the mask. By contrast, there were no observable threading dislocations in the overgrown portions of the layer. The few dislocations observed formed parallel to (0001) plane via the extension of the vertical threading dislocations after a 90š bend in the regrown region. They did not subsequently propagate to the surface of the overgrown GaN layers. Recently we have pioneered a new process route to selective epitaxy of GaN and AlxGa1-xN layers with a low-defect density, namely, pendeo (from the Latin: to hang or be suspended from)-epitaxy (PE). It incorporates mechanisms of growth exploited by conventional lateral growth processes by using masks to prevent vertical propagation of threading defects, and extends the phenomenon to employ the substrate itself as a pseudo-mask. The growth does not initiate through open windows, rather it begins on sidewalls of forms etched into a seed layer and continues until coalescence over and between the seed structures occurs, resulting in a single complete layer. The PE growth of GaN and AlGaN alloys via MOVPE and the use of silicon nitride and nickel etch masks has been the focus of this investigation. The three main stages of PE growth, namely (i) initiation of selective lateral homoepitaxy from the seed sidewalls of the nitrides, (ii) vertical growth and (iii) lateral growth over the silicon nitride masked seed structure to form both discrete microstructures and coalesced single crystal layers will be described for these materials. These processing procedures and the aforementioned stages will be presented in tandem with supporting structural, microstructural, optical and electrical evidence.

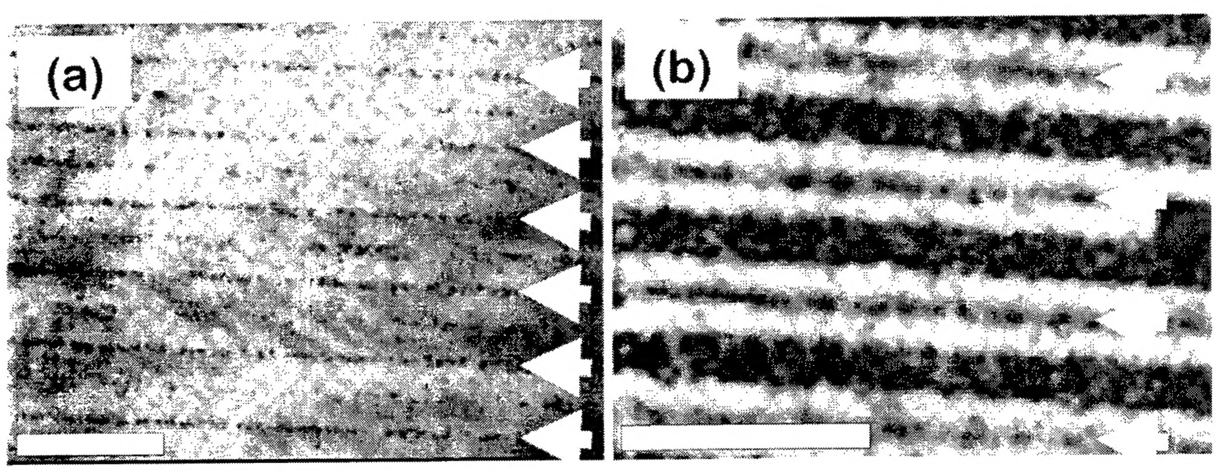
This work was supported by the Office of Naval Research under contracts N00014-96-1-0765 (C. Wood, monitor) and N00014-98-1-0122 (J. Zolper, monitor).

A Two Step Process for Epitaxial Lateral Overgrowth of GaN

B. Beaumont, P. Gibart
CRHEA-CNRS, Parc Sophia Antipolis
F06560 Valbonne France

We report on a modified process for the epitaxial lateral overgrowth of GaN. In the first step, the overgrowth proceeds at low temperature and due to the low lateral over vertical growth rates ratio, GaN stripes with a triangular cross section are rapidly obtained. This first step is particularly attractive since in the GaN seed so grown, threading dislocation bow out to the free {11-22} free sidewalls. Once these triangular stripes are completed, the growth conditions are changed either by increasing the growth temperature or by introducing Mg precursor. Then coalescence and flattening take place.

A comparison, based on TEM plane view and cathodoluminescence (CL) mapping, between samples grown with both processes evidences a further improvement in the threading defects distribution with this two-step process. Particularly, the defect density in the seed region is no more matching that of the underlying GaN template, due to the defect lines bending in the GaN overgrown above the windows. This is illustrated in the following cathodoluminescence (l=358 nm, 90K) maps. In (a) is the CL of a two-step process ELO GaN sample to be compared to that of a single step ELO one in (b), both grown with the same mask geometry (10 µm period, 3µm windows). The marker is 20 µm on these images. White arrows indicates the coalescence boundaries.



Lateral Epitaxial Overgrowth Using Alternative Sources

L. Zhang, D.M. Hansen, K. Dunn*, S. E. Babcock*, and T. F. Kuech
Department of Chemical Engineering,
*Materials Science and Engineering Department
University of Wisconsin-Madison, WI, 53706

Marek P. Boleslawski, Aldrich Chemical, Milwaukee, WI.

Lateral overgrowth epitaxial (LEO) of GaN was investigated using trimethyl gallium (TMGa) and diethyl gallium chloride (DEGaCl) sources under comparable growth conditions in a MOVPE reactor. DEGaCl allows for the development of the hydride vapor phase epitaxy growth conditions near the growth front allowing for high lateral growth rates. SEM, TEM and AFM have been used to characterize the facet information, surface morphology and defect structure. High growth temperatures and high V/III ratios result in higher lateral growth rate for openings aligned along the <1-100> direction and vertical and sloped facets can be produced by changes in the reactor operating conditions. The DEGaCl leads to smoother, less jagged facets when compared to TMGa-based growth. Jagged facets lead to a high defect density at the point of coalescence, as revealed by TEM. LEO GaN using DEGaCl source has smaller kink density, favorable for fast and smooth coalescence under conditions of a high V/III ratio required for improved materials properties. The different in LEO behavior for the two Ga sources is discussed in terms of the chloride-based growth chemistry and existing models of HVPE growth.

Electrical and Structural Properties of GaN Laterally Overgrow on GaN/Al_2O_3 and AlN/Si(111) Substrates

H. Marchand, J.P. Ibbetson, P.T. Fini, N. Zhang, L. Zhao, Y. Golan, B. Moran, S. Keller, J.S. Speck, S.P. DenBaars, U.K. Mishra
Electrical & Computer Engineering and Materials Departments,
University of California, Santa Barbara, CA 93106

The lateral epitaxial overgrowth (LEO) technique has been shown to be very promising for improving the properties of GaN films grown on sapphire, silicon carbide, and silicon substrates. In this presentation we review the structural and electrical properties of LEO GaN deposited on sapphire and silicon substrates.

For growth on sapphire the seed layer for the LEO consisted of a SiO_2-masked 2 μm-thick GaN films grown on c-plane Al_2O_3 by metalorganic chemical vapor deposition (MOCVD) using a conventional two-step process. The density of threading dislocations (TD) in such layers is typically 10^8-10^9 cm^{-2}. The GaN stripes laterally overgrown using a vertical-sidewall morphology have a TD density of 10^5-10^6 cm^{-2} owing to very efficient blocking of TDs from the seed layer by the SiO_2 mask. New edge dislocations are created above the mask edges and at the coalescence fronts and are related to a crystallographic tilt of the LEO regions relative to the seed crystal. The density of those residual defects can be minimized by careful control of the LEO stripe morphology.

The growth on silicon substrates is complicated by the large thermal expansion mismatch which puts the GaN under large tensile stress and results in cracking. Typically a ~1 μm-thick GaN film necessary to achieve a starting TD density <10^{10} cm^{-2} is cracked following cooldown when grown on a two-inch Si(111) wafer. To minimize the amount of tensile stress and avoid the formation of cracks prior to regrowth, the LEO of GaN was initiated from a SiO_2-masked AlN buffer layer. This process also yields LEO GaN stripes with ~10^5-10^6 cm^{-2} TDs, but new mixed-character dislocations with line directions in the basal plane are generated due to the presence of jagged or inclined sidewalls. Stripes narrower than ~10 μm are not cracked but wider stripes exhibit cracking, which must be accounted for in designing device structures.

The presentation will address the morphological evolution of LEO stripes, structural and electrical characterization, and remaining challenges of LEO both on sapphire and silicon substrates.

This work is supported by ONR-ACI under the supervision of Dr. C. Wood.

Lateral Epitaxial Overgrowth vs. Pendeo-Epitaxy of GaN Structures - A Finite Element Analysis

Tsvetanka Zheleva, Waeil Ashmawi*, and Kenneth A. Jones
Sensors and Electron Devices Directorate, US Army Research Laboratory,
Attn:AMSRL-SE-EM, 2800 Powder Mill Road, Adelphi, MD 20783, USA
* Department of Mechanical Engineering, North Carolina State University, Box 7907, Raleigh, NC 27695-7907

Recent studies on selective growth of GaN structures via conventional lateral epitaxial overgrowth (LEO) and pendeo-epitaxy (PE) on 6H-SiC substrates [1-3], as well as sapphire substrates [4,5], unambiguously revealed that the regions of lateral growth exhibit four-to-five orders of magnitude lower density of dislocations compared to the regions of vertical growth. The above phenomenon is successfully utilized in novel blue laser diodes with drastically improved life times [6,7]. However, it is still not clear why and how the change of the growth direction of the selectively grown GaN from vertical to lateral in both LEO and PE enables this drastic reduction in the defect density. The most probable explanation is the free-standing lateral growth in pendeo-epitaxial GaN structures, as well as the quasi-free-standing lateral GaN growth during the conventional LEO process and the associated stress reduction. In both cases the crystallographic template (the matrix) for the lateral growth are the $\{11\underline{2}0\}$, $\{1\underline{1}00\}$, or the $\{1\underline{1}01\}$ side facets of the GaN. Analysis of the experimental data of time and temperature dependence of the propagation of the vertical and lateral GaN growth fronts, and examination of the morphology of the top surfaces, side facets, and interfaces of the LEO- and PE-GaN stripes with the underlying and adjacent interfaces, reveals their strong correlation with the diffusion related characteristics of the adatom species. It is also evident the strong correlation between the repeatedly observed in transmission electron microscope (TEM) morphologies of the side and top surfaces and interfaces and the thermally generated stress/strain gradient profiles as calculated via finite element analysis (FEA) [8]. A comparison between the stress distribution as a result of the mismatch in the coefficients of thermal expansion among the films in the structures, grouped in four types with different geometries will be presented: 1) conventional LEO-GaN; 2) conventional LEO-GaN without SiO_2 mask; PE-GaN - mode A; and 4) PE-GaN - mode B. The range in stresses is least in the conventional LEO - GaN geometry with the SiO_2 mask layer removed - from compressive of 2.6 GPa to tensile of 0.45 GPa, opposing to the maximum range of stresses in PE-GaN mode A geometry - from compressive of 3.8 to tensile of 0.6 GPa. Stresses in all, but the conventional LEO-GaN geometry, are localized within the window/GaN column regions. The role of the (i) window width (LEO - case) or GaN column width (PE case); (ii) LEO/PE GaN stripe width; and (iii) the thickness of the LEO/PE GaN layer will be discussed in therms of tendencies for stress reduction.

[1] T. Zheleva et al., Appl. Phys. Lett., 71 (17), 2472 (1997).
[2] T. Zheleva et al., MRS Internet J. Nitride Semiconductor Res., 4S1, G3.38 (1998).
[3] T. Zheleva et al.,J. Electr. Mater., 28 (4), L5 (1999).
[4] A. Sakai et al., Appl. Phys. Lett., 71, 2259 (1997).
[5] H. Marchand et al., MRS Internet J. Nitride Semiconductor Res., 3, 3 (1998).
[6] S. Nakamura et al., Appl. Phys. Lett., 72, 211 (1998).
[7] S. Nakamura et al., Jpn. J. Appl. Phys, 38, Part 2 (3A) L227 (1999).
[8] T. Zheleva et al., J. Appl. Phys., 74 (17), 2492 (1999).

LEO of III-Nitride on Al_2O_3 and Si Substrates

M. Razeghi, P. Kung, D. Walker, P. Sandvik, M. Hamilton, K. Mi, X. Zhang and J. Diaz
Center for Quantum Devices, Department of Electrical and Computer Engineering,
Northwestern University, Evanston, IL 60208

Yanguo Wang, Steve Kim and Vinayak P. Dravid
Department of Materials Science and Engineering, Northwestern University, Evanston, IL 60208

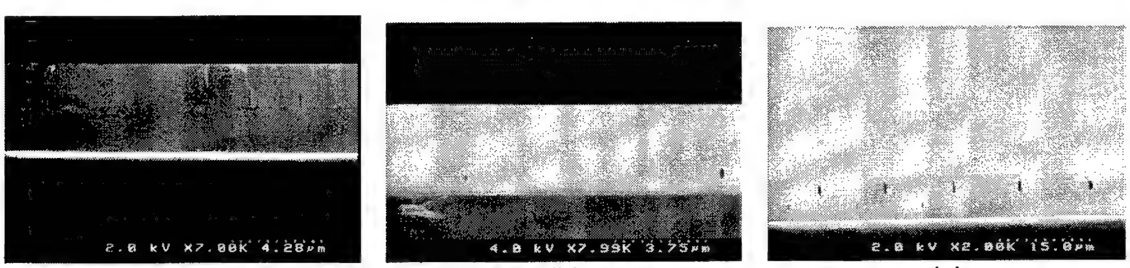
J. Freitas
Naval Research Laboratory, Washington, DC 20375-5347

Lateral epitaxial overgrowth (LEO) has recently become the method of choice to reduce the density of dislocations in heteroepitaxial GaN thin films, and is thus expected to lead to enhanced performance devices.

We present here the LEO growth and characterization of GaN films by low pressure metalorganic chemical vapor deposition. Various substrates were used, including basal plane sapphire and (111) oriented Si substrates. The steps in the LEO growth technology will be described. The characterization results will be discussed. The structural, optical and electrical properties of the films were assessed through x-ray diffraction, scanning and transmission electron microscopy (SEM, TEM), atomic force microscopy (AFM), photoluminescence, scanning cathodoluminescence, Hall and capacitance-voltage measurements.

Similarly high quality LEO grown GaN films were achieved on sapphire and Si substrates. Figure 1 (a) and (b) show the cross-section SEM micrographs of a fully coalesced single LEO grown GaN on sapphire and Si substrates. The x-ray diffraction spectra generally exhibited three peaks for the GaN, which suggests that the LEO grown GaN was strained differently than the underlying template layer. The photoluminescence from these wafers strong bandedge excitonic emission at 300 K and 77 K with negligible deep level emissions. Atomic force microscopy showed that the "laterally grown" GaN over the dielectric mask was smoother and contained fewer threading dislocations than the "vertically grown" GaN in the mask opening windows. *TEM analysis, using focused ion beam (FIB) site-specific sectioning, was utilized to **quantitatively** understand the propagation, deviation and reduction of threading dislocations in the laterally grown GaN*. In an effort to further reduce extended defects, "double LEO" was conducted as shown in the cross sectional SEM micrograph in Figure 1 (c). Additional characterization results will be presented.

This work was supported by the Office of Naval Research under grant No. N00014-98-1-0403 and monitored by Dr. Colin Wood.



(a) (b) (c)

Figure 1. Fully coalesced single LEO grown GaN on (a) sapphire and (b) Si substrates; and fully coalesced double LEO grown GaN on sapphire substrate.

Maskless Dislocation Reduction in GaN Films

S. Keller, G. Parish, S. P. DenBaars, and U. K. Mishra
Electrical & Computer Engineering and Material Departments, University of California, Santa Barbara, CA 93111

D. Kapolnek, P. Parikh
WideGap Technology LLC, 107 S. La Patera Lane, Goleta, CA 93117

Dislocation reduction in GaN films grown on sapphire and silicon substrates was observed after insertion of thin InGaN layers grown in a selective spiral island growth mode. Utilizing this method, GaN on silicon films with a full width at half maximum (FWHM) of 800 arcsec were fabricated, in comparison to a FWHM of 1280 arcsec without InGaN interlayers.

The GaN films were grown by MOCVD in the standard two step growth process. On sapphire, the growth was initiated with the deposition of an approximately 20 nm thick GaN nucleation layer; on silicon it was initiated with an AlN nucleation layer. The growth temperature of the main GaN layer was 1070 °C. After deposition of about 1 μm of GaN, the GaN growth was stopped and the surface exposed to disilane, resulting in the deposition of submonolayers of Si_xN_y. Previous investigations had shown that this treatment partially passivates the GaN surface, so that InGaN layers deposited afterwards grow in a selective spiral growth mode around threading dislocations with screw character, if grown at a low growth rate. In this study, 10 nm $In_{0.1}Ga_{0.9}N$ layers were deposited at 790 °C at a growth rate of 0.2 Å/s. Afterwards, the growth temperature was increased to 1070 °C and the GaN growth continued. The epitaxial layers were characterized by X-ray diffraction, atomic force microscopy and photoluminescence measurements. Data on the effect of the Si_xN_y layer thickness and the number of inserted InGaN layers will be presented.

In the case of GaN layers grown on sapphire, which exhibited a much higher initial crystalline quality than the GaN films grown on silicon, the insertion of InGaN layers resulted mainly in a reduction of the FWHM of the (102) reflection, corresponding to a reduced number of edge dislocations. As the InGaN spiral islands are seeded at dislocations with screw character, they can overgrow edge dislocations only. In the case of the growth on silicon, where the initial GaN "grain density" is much higher, and a higher number of grains without screw dislocations exist, the probability of grain overgrowth is increased and the dislocation reduction more efficient.

Although resulting only in a gradual dislocation reduction, the presented method is of interest for applications that do not require complete dislocation elimination, for instance for devices operated under forward bias conditions. The advantages are simple layer insertion, short growth time and no processing.

[1] S. Keller, U. K. Mishra, S. P. DenBaars, W. Seifert, Jpn. J. Appl. Phys. 37 (1998) L431

The Application of Nanoheteroepitaxy to the OMVPE Growth of GaN on Silicon

S.D. Hersee, D. Zubia, S. Zaidi, S.R.J. Brueck
Center for High Technology Materials and EECE Department,
University of New Mexico, Albuquerque, NM

This paper will describe recent progress in the application of nanoheteroepitaxy to the growth of GaN on <111> SOI (silicon on insulator) substrates. Nanoheteroepitaxy (NHE) is a new approach to the heteroepitaxial growth of mismatched semiconductor materials, which exploits 3-D stress relief mechanisms available to nanoscale (10 - 100 nm) islands. In practice NHE consists of a nanostructured substrate (in this case a patterned <111> SOI substrate) and a selectively grown (GaN) epilayer. The small size of the nanoscale GaN on Si islands during selective growth allows them to undergo 3-D stress relief before coalescence, which eventually occurs through lateral growth of the GaN. The net result is an increase in the critical thickness for pseudomorphic growth. In the case of GaN on Si, experiments indicate that there is also a size induced lowering of the silicon melting point, which further enhances the compliance of the SOI substrate. This paper will briefly describe the theory of NHE then show SEM and XTEM analysis of NHE grown GaN on nanostructured <111> SOI substrates. Particular emphasis will be placed on the location, structure and density of defects. GaN grown on patterned SOI and conventional planar SOI will be compared.

We anticipate that the NHE approach will be widely applicable to many heterogeneous systems including; Ge/Si, InGaAs/GaAs, GaAs/Si and GaN/sapphire and GaN/Si. In the case of extremely mismatched systems, such as GaN on Si, where the complete elimination of defects may not be possible, we anticipate that NHE will achieve significant reductions in defect density.

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Properties of Undoped and Doped (Mg, Be, Er) Bulk GaN Crystals Obtained by High Pressure Synthesis

T. Suski
UNIPRESS, Polish Academy of Sciences, Sokolowska 29, 01-142 Warsaw, Poland

The main purpose of introducing lateral epitaxial overgrowth (LEO) technique was to reduce a concentration of extended defects caused by lattice and thermal expansion mismatches between epitaxial films and substrates. In this context, substrates made of bulk GaN crystals are ideal for epitaxy of gallium nitride based semiconductors.

GaN crystals grown at high pressures and temperatures (1.4 GPa, 1500°C) from pure liquid Ga are conductive with free electron concentration of the order of $5 \bullet 10^{19}\,cm^{-3}$. The most probable source of free electrons is oxygen impurity substituting nitrogen in GaN crystal matrix. Though, these highly conductive single crystals with lateral dimensions approaching 15 mm, are very suitable for optoelectronic applications, there is a need to have highly resistive substrate material also. Moreover, from the point of view of controlling electrical/optical properties of bulk GaN it is desirable to grow crystals characterized by wide range of electron/hole concentrations.

Doping of bulk GaN with erbium leads to a decrease of electron concentration to about $1 \bullet 10^{19}$ cm^{-3}. Beryllium doped crystals are semiinsulating. Whereas, increasing an amount of Mg added into the liquid Ga during the growth results in three types of GaN:Mg crystals: i) n-type, highly conductive, ii) highly resistive, and iii) p-type with low hole concentration. With further increase of Mg content a growth of new compound (Ga,Mg)N might occur. It crystallizes in the hexagonal P3 structure with the unit cell tripled in the direction of c-axis (with respect to GaN).

In the present talk some interesting physical properties of the above described crystals will be discussed. Then, selected results illustrating a homoepitaxial growth will be given.

Dislocation Mechanisms in the GaN Lateral Overgrowth by Hydride Vapor Phase Epitaxy

T. S. Kuan and C. K. Inoki
Department of Physics, State University of New York at Albany, Albany, NY 12222

T. F. Kuech and S. Gu
Department of Chemical Engineering, University of Wisconsin, Madison, WI 53706

Electron microscopy was used to investigate the dislocation structure and mechanisms involved in lateral epitaxial overgrowth (LEO) of GaN using the hydride vapor phase epitaxy technique. The growth morphology is most sensitive to the growth temperature. High lateral growth rate at 1100°C allows coalescing of neighboring islands into a continuous and flat film, while the lower lateral growth rate at 1050°C produces triangular-shaped ridges over the growth windows. In either case, threading dislocations bend into laterally grown regions to relax the shear stress developed in the film during the growth. In regions of maximum shear stress, dislocations interact and multiply into arrays of edge dislocations lying parallel to the growth window. This multiplication and pileup of dislocations cause a large-angle (3 to 10 degrees) tilting of the laterally grown regions. Stress simulations suggest that the thermal stress at the oxide mask edge and the high tensile stress present in the seed layer can cause the observed excessive dislocation activities during the high-temperature lateral growth.

Advantages and Problems of Lateral Overgrowth of GaN Layers

Z. Liliental-Weber , M. Benamara, and J. Washburn, Materials Science Division, Lawrence Berkeley National Laboratory, Berkeley CA 94720, 62/203

J. Park, P. A. Grudowski, C. J. Eiting and R. D. Dupuis, Microelectronics Research Center, The University of Texas at Austin, Austin TX 78712-1100

J.Freitas, Naval Research Laboratory, Washington DC

R. F. Davis, North Carolina State University, Raleigh NC 27695-7907

S. Nakamura, Nichia Chemical Industries Ltd., Tokushima 774, Japan

Transmission electron microscopy was applied to study defects in GaN films grown by lateral epitaxial overgrowth (LEO). The GaN LEO layers are grown by MOCVD on GaN heteroepitaxial films previously grown either on (0001) sapphire or SiC. The silicon dioxide 100 nm thick masks were patterned with parallel stripes along the [100] direction. The isolated and coalesced "pendeo" layers formed by lithographical etching of GaN with Al2O3 protective masks followed by similar lateral growth over silicon dioxide masks have been also studied.

Much lower densities of defects and different arrangement of defects is observed in the overgrown parts of the layers compared to the heteroepitaxial growth. However, misorientation between particular parts and flatness of the top layer appear as the main problems of lateral overgrowth.Typical defects in the overgrown areas are bending dislocations with a large component parallel to the basal planes and some faulted prismatic dislocation loops. Helical dislocations were also observed in the overgrown areas with axis oriented along the c direction. They were mostly formed close to the edges where the lateral growth initiated and were associated with a high concentration of impurities. Dislocations formed in this areas accommodate the tilt which occurs between the homoepitaxial part of the layer and the overgrown part of the layer. In the areas where two lateral overgrowth fronts meet there is formation of a small-angle grain boundary consisting of a array of dislocations. A small cavity or void at this growth meeting front is also observed an almost every sample. The structural quality for pendeo epitaxy and LEO growth on sapphire and SiC appear to be very similar.

Presenting and Contact Author:
Zuzanna Liliental-Weber (e-mail: z_liliental-weber@lbl.gov)
Lawrence Berkeley Laboratory, MS 62/203
One Cyclotron Road
Berkeley, CA 94720, Tel.: 510 468 6254, Fax.: 510 486 4995

Epitaxial Lateral Overgrowth by Hydride VPE

Akira Usui
Optoelectronics and High Frequency Device Research Laboratories,
NEC Corporation, 34 Miyukigaoka, Tsukuba, Ibaraki 305-8501, JAPAN

Introduction

We have first proposed epitaxial lateral overgrowth (ELO) for growing thick GaN layer which can be used as a substrate [1]. As expected from previous studies of ELO such as GaAs/Si [2], the dislocation density was surely reduced. However, the dislocation reduction mechanism was not the same as that of the previous ELO from precise TEM observations. We found that facet structure formation at the beginning of the growth plays a very important role to suppress threading dislocations [3,4] and thus named it facet-initiated ELO (FIELO). In this paper, we report several-hundred-micron-thick GaN layers on a sapphire substrate using the FIELO method. Thick-layer growth is considered to contribute to the further reduction of the dislocation density and to the preparation of free-standing GaN crystals.

Experimental

Hydride VPE(HVPE) method was used to grow FIELO GaN. GaCl partial pressure was varied in the 5.2-13x10^{-3} atm range. The NH_3 was varied in the 0.13-0.53 atm range. The total flow rate including the H_2 carrier gas was 3,800 sccm. The substrate temperature was about 1050°C. 2-inch-diameter sapphire wafers with a 1- to 1.5 μm-thick GaN layer on top was used as the substrates. Window stripes aligned along the <11-20> direction of the GaN layer were fabricated on this wafer by using SiO_2. The width of mask region was 3 μm and the width of the window region was 4 μm.

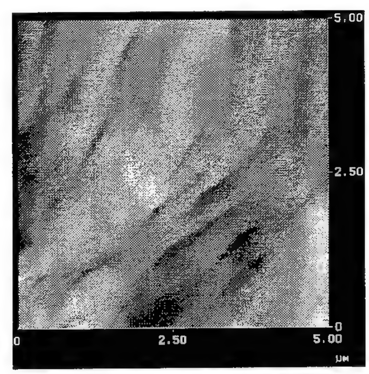

Fig. 1 AFM image of FIELO GaN surface grown at 120 μm/h.

Results and Discussion

First, we optimized growth conditions in order to obtain a high-growth rate without the degradation of crystal quality. The growth rate increased by increasing both GaCl and NH_3 partial pressures and reached about 200 μm/h under the following growth conditions; GaCl partial pressure of 1.3x10^{-2} atm, NH_3 partial pressure of 0.53 atm and the growth temperature of 1040°C. No cracks were observed under Normarski microscope observation for samples having a thickness of 100-500 μm. Figure 1 shows an AFM image of a sample grown with the growth rate of 120 μm/h. The atomic step image indicates that the step-flow growth mode can be clearly observed even under such a high growth-rate condition.

Figure 2 shows the grown thickness dependence of etch-pit density (EPD). We have already reported the decrease of the EPD by increasing the grown thickness up to 150 μm [3]. It was clearly shown in Fig. 2 that the further increase of the grown thickness resulted in the further decrease of the EPD. The lowest EPD obtained in this experiment was 8x10^6 cm^{-2}. The EPD reduction may attribute to the formation of closed loops by a part of threading dislocations

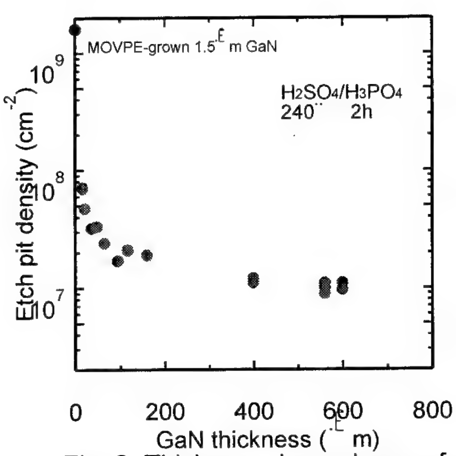

Fig. 2 Thickness dependence of etch pit density.

during the growth. Some dislocations are also considered to bend their directions and to go out of crystal.

The thickness uniformity was evaluated for about 100-μm-thick FILEO GaN layers. We found that the uniformity depends on the length of the mixing zone where GaCl and NH_3 were mixed. By optimizing this length, the best uniformity was found to be ±3% over 2-inch-diameter wafer except 5mm-wide edge region.

Conclusion

We studied the growth of several-hundred-micron-thick GaN layers on 2-inch-diameter sapphire substrates by HVPE with the FIELO method. No degradation was observed on the surface morphology up to the growth rate of 120 μm/h. As a result, a 500-μm-thick GaN layer was successfully grown without the generation of cracks. The EPD was reduced to $8\times10^{6}cm^{-2}$ by growing a 560-μm-thick GaN layer

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Mask-free Nano-size Epitaxial Lateral Overgrowth (NELOG) Technique for GaN and SiC

Marina Mynbaeva and Vladimir Dmitriev*

Ioffe Institute and Crystal Growth Research Center, St. Petersburg, Russia

* TDI, Inc., Gaithersburg, MD 20877

We report on a novel technique aiming the defect density and stress reduction in wide band gap epitaxial and bulk semiconductor materials. Lateral epitaxial overgrowth was performed by hydride vapor phase epitaxy for GaN and by vacuum sublimation epitaxy for SiC. GaN layers were grown on GaN/SiC epitaxial wafers (substrates) and SiC layers were grown on SiC substrates. Prior the overgrowth, nano-size surface relief was formed on GaN and SiC substrates. It was shown that GaN and SiC overgrown layers have a good surface morphology and high crystal quality. The surface of overgrown material was uniform and flat. X-ray, photoluminescence, and Raman spectroscopy measurements indicated that stress and defect density were significantly reduced in the overgrown layers. Material characteristics will be presented. The method will be discussed in terms of possible applications for bulk and epitaxial growth. It is important to note that the NELOG technique does not require any mask. This technique may be easily scaled for large area substrates.

Lateral MBE Growth of GaN on Patterned GaN/Sapphire

A.M. Dabiran,[a)] M.R. Hoit, B.E. Ishaug, R. Held, and P.I. Cohen,
Deptartment of Electrical and Computer Engineering, Univ. of Minnesota, Minneapolis, MN

a) and Silver Sky Technologies, Inc., St. Paul, MN

Lateral epitaxial overgrowth (LEO) of GaN provides films with reduced defect density, better electrical and optical properties, and substantial improvements in device performance. All of the reported results on this technique to date have been based on material overgrown using MOCVD on patterned masks. In this talk, we present the results of our study on the LEO of GaN directly on sapphire using molecular beam epitaxy (MBE). Under proper growth conditions, LEO is shown to proceed from the sidewalls of features etched in thin GaN films without nucleating GaN on the exposed sapphire.

To prepare the patterned GaN film, a mask was placed on a thin (~ 15 nm) GaN(000$\underline{1}$) film grown by MBE on a sapphire substrate. The pattern consisted of 1 mm by 2 mm rectangular regions of 1.5 micron spaced, 2 micron wide lines and of pinwheels with 4 and 6 micron wide and 100 micron long lines every 15 degrees. The pattern was etched through the thin GaN down to the sapphire substrate using a chlorine/argon chemistry in an RF reactive ion etcher. Before starting the overgrowth, the exposed sapphire surface was recleaned with a standard sapphire etch which does not attack the patterned GaN. The sample was then loaded into the MBE system and an approximately 300 nm of GaN, as measured by AFM, was grown on the patterned GaN surface. The growth was carried out under a Ga-rich conditions and at a temperature well above the condensation temperature of Ga on GaN as determined by desorption mass spectroscopy (DMS). In this growth regime no new GaN nucleation occurs on the exposed sapphire regions. Instead, highly mobile Ga adatoms diffuse to and are incorporated at the sidewalls of the patterned GaN film resulting in LEO growth.

The LEO layer grown in this way was characterized using atomic force microscopy (AFM), scanning electron microscopy (SEM), and spatially resolved cathodoluminescence (CL). AFM and SEM results showed a anisotropic lateral to vertical growth ratio of about 3:1 in the optimum lateral growth direction. Also, an improvement in the optical quality of the LEO material was shown by the enhancement of band-edge emission, and a reduction of yellow-green emission. AFM and SEM images of the pinwheel pattern regions also indicated no nucleation of GaN on the exposed sapphire regions.

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The Influence of Active Nitrogen Species on High Temperature Limitations for GaN Growth by RF-Plasma Assisted Molecular Beam Epitaxy

T.H. Myers[(a] and A.J. Ptak
Department of Physics
West Virginia University
Morgantown, WV 26506

Growth of GaN by molecular beam epitaxy (MBE) is typically limited to temperatures less than 750 °C due to increased desorption of Ga from the growing surface, resulting in a greatly reduced growth rate. The temperature for the onset of this decreased growth rate varies from group to group, and is typically lower than expected based on thermal decomposition rates for GaN. In addition, we have shown[1] that atomic hydrogen can be used to stabilize the growing surface. We will report on the relative reactivity of the various active nitrogen species produced by rf plasma sources: low and high energy ions, atoms and metastables. Reactivity is determined based on low temperature (~400°C) nitridation rates for sapphire. Studies of growth rate as a function of temperature suggest the GaN surface is prone to "attack" by neutral and ionic atomic nitrogen above 700°C, promoting decomposition. This leads directly to the observed lower than expected temperature for a significant decrease in growth rate, while this decrease is not observed when the active nitrogen flux consists primarily of nitrogen metastables. Dramatically improved electrical properties are observed in epilayers grown using nitrogen metastables. Growth kinetics for both (0001) and (000$\underline{1}$) GaN surfaces will be discussed.

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Email: [(a]tmyers@wvu.edu

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Addressing the GaN Substrate Problem with Ammonia-based MBE

Gary W. Wicks
University of Rochester

Since large area, high quality GaN substrates are not available for GaN epitaxy, other approaches have been developed. This work addresses two such approaches that are being examined with ammonia-based MBE. Selective-area growth / lateral epitaxial overgrowth is one approach that has been widely used in MOCVD but, so far, not in MBE. Another possible approach is lifting thick GaN epitaxial layers off their initial substrates, for subsequent use as GaN substrates.

Selective-area growth works well in MOCVD because of the material-dependent cracking efficiencies of the source molecules, *i.e.*, cracking is efficient on III-N surfaces but inefficient on silicon dioxide or silicon nitride surfaces. Plasma-based MBE growth of III-N's does not lend itself well to selective-area growth because there is no cracking of source molecules. Ammonia-based MBE, like MOCVD, *does* depend on cracking (of the ammonia molecule). If this cracking is material-dependent, there is a possibility that ammonia-based MBE can selectively grow GaN in openings in inert masks. This work has experimentally measured, in an MBE environment, ammonia cracking efficiencies on surfaces of several different materials. Ammonia cracks 1-2 orders of magnitude more efficiently on reactive surfaces such as GaN and AlN, than on inert surfaces such as sapphire.

Liftoff of GaN epitaxial layers from the substrate is difficult if the substrate is sapphire, since the substrate cannot easily be selectively etched away. Silicon or GaAs substrates can easily be selectively etched from GaN, but GaN epitaxial layers on these substrates typically crack upon cooling from the growth temperature due to differential thermal contraction. Lower growth temperatures is the solution to the cracking problem. This work examined the growth temperature dependence of crack densities in 1.5 micron thick GaN layers grown by ammonia-based MBE. Crack densities were found to decrease dramatically as the growth temperature is lowered from 800C to 750C, vanishing completely at growth temperatures of 700C and lower.

Nitride Semiconductors and MBE

Hadis Morkoç
Virginia Commonwealth University
Department of Electrical Engineering and Physics Department
601 W. Main Street
P. O. Box 843072
Richmond, VA 23284-3072
FAX: (804) 828-4269
TEL: (804) 827-3765
e mail: hmorkoc@vcu.edu
http://www.vcu.edu/egrweb/vmc/research/index.html

In the last few years, there appears to have been a subterranean current among more than a few that MBE does not have a role to play in nitride semiconductors, even at the research level. This is not something new as similar statements were made in the heydays of III-V research, even though MBE was clearly the leader. Industrial trends of past several decades have proven that assertion wrong.

In this presentation, the evolution of MBE as germane to nitride semiconductors, the current status, and eminent developments will be discussed.

Application of LEO Technique for the ZnTe/CdTe Growth and Its Use in Enhancing Army's Capabilities in the Next Generation HgCdTe Based Infrared Focal Plane Arrays

N. K. DHAR
Army Research Laboratory

The next generation of Infrared Focal Plane Array (IRFPA) needs many additional features over the present state-of-the-art IRFPAs. Paramount among these features is the capability to produce very large dimension arrays (1024x1024). Additionally, the possibility of fabricating monolithic designs with additional multicolor and multi-domain sensing capabilities would advance IRFPA technology to meet Army's future needs. To be able to realize large arrays, high quality large substrates that are thermally compatible to the read-out multiplexer processors are needed. Current bulk CdZnTe substrates do not meet specifications necessary for developing large as well as monolithic IRFPAs. Alternative substrates such as Si based composite structures can provide both, a thermally reliable substrate for large arrays in hybrid configuration, and also allows monolithically designed IRFPA structures. However, the present Si based composite substrates contain high density of defects due to the large lattice mismatch and electronic charge differences at the interface between CdZnTe/HgCdTe and Si substrates. This clearly makes it very difficult to fabricate even smaller arrays. In this work we exploit the lateral epitaxy overgrowth (LEO) technique to reduce the defect density in the CdTe buffer layers. Thin (100-300 Å) layers of Silicon Nitride and Silicon di-oxide were used as masked regions with open windows exposing CdTe seeding layer. Migration enhanced epitaxy was employed to improve surface diffusion lengths and to encourage nucleation at the peripheral regions of the seeding layer. Over layers of epitaxial Si was also used to study the LEO process. It was found that arsenic passivation reduces the Te_2 sticking coefficient significantly. The major problem encountered was the ability to clean initial masked sample. Layer characteristics such as dislocation density, x-ray rocking curve and surface morphology will be discussed, and possible improvement in the MBE growth technique using LEO will be discussed.

Radiative Recombination in InGaN/GaN Multiple Quantum Wells

B Monemar
Dept of Physics and Measurement Technology, Linköping University, S-58183 Linköping, Sweden

H Amano and I Akasaki,
Meijo University, 1-501 Shiogamaguchi, Tempaku-ku, Nagoya 468, Japan

Radiative recombination processes in InGaN/GaN multiple quantum wells (MQWs) are of considerable interest, due to the application in LEDs and LDs. In this work we have studied structures with an In composition close to x = 0.15, with different thickness of the QWs. Samples grown under different conditions, such as different InGaN growth temperature, have been studied and compared. The large Stokes shifts between the broad PL peak and the graded band edge in PLE spectra is mainly attributed to the strong Stark shift caused by the piezoelectric field, which can be screened by Si doping, or by a high excitation intensity. The broad PL linewidth is a measure of the potential fluctuations in the system. These are also strongly influenced by donor doping and carrier injection. Both excitons and free carriers are believed to be involved in the recombination. This leads to a wide range of nonexponential decay times, which we have studied on a time scale from 10 ps to 4 microseconds, between 2 K and 300 K. Most samples show a single PL peak, but in some samples more than one PL peak occurs in time-resolved spectra. In such cases the peaks have drastically different time decay. We will attempt to provide a unified description of the recombination processes in different samples, related to the structural properties.

Optical and Electronic Properties of Lateral Epitaxial Overgrown GaN Layers

Jaime A. Freitas, Jr., Naval Research Laboratory
Washington, DC 20375

Although reliable electronic and opto-electronic devices have been fabricated with state-of-the-art GaN films, their performance remains limited by material properties. The high density of dislocations and the lack of control of doping and compensation seem to be directly and/or indirectly associated with the film-substrate lattice mismatch and/or the mismatch of the thermal expansion coefficients. Selectively grown GaN films have been deposited on GaN heteroepitaxial layers in order to reduce the usual high density of structural defects in hetero-epitaxial layers. TEM studies of the rectangular cross-sectional overgrown layers, obtained for mask apertures oriented along $\langle 1\bar{1}00 \rangle$, show that the dislocations present in the underlying GaN substrate propagate through only the regrown GaN directly above the stripe-patterned substrate (window regrown - WR), whereas the lateral epitaxial overgrown (LEO) GaN has a substantially reduced density of threading dislocations [1]. Spatially resolved room temperature Raman scattering experiments performed on the LEO layers suggest that they have lower biaxial strain and structural defect concentration than the WR GaN region [2].

Low temperature photoluminescence (PL) spectroscopy was applied to investigate the nature of the recombination processes in the WR and LEO regions. High-resolution photoluminescence spectra of the bandedge emission bands exhibit the free-exciton line and at least two shallow donors related lines. The line at ~ 3.4667eV is the pervasive native donor which is commonly observed in undoped films. Based on our previous work we assign the line at ~ 3.4643eV to recombination of excitons bound to neutral Si-donors [4]. This Si-doping may originate from the incorporation of thermally released Si-ions from the SiO_2 mask used for substrate patterning. Time resolved PL measurements were used to investigate the nature of the emission band at 3.263eV. This band, present mostly in the LEO region, was assigned to recombination processes involving shallow-donors and shallow-acceptors. Secondary electrons and real color catholuminescence imaging techniques were applied to investigate the areal distribution of recombination processes in different regions of the homoepitaxial layer. Similar work performed on homo-epitaxial layers fabricated by pendeo-epitaxial technique will be presented.

This work was done in collaboration with R.F. Davis, O.H. Nam, T.S. Zheleva, T. Gehrke, S.K. Obyden, and G.V. Saparin.

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GaN Lateral Epitaxial Overgrowth (LEO) on Sapphire and Silicon Substrates and Recent Device Results

S. P. DenBaars, H. Marchand, M. Hansen,G. Parish ,P. Fini, T. Katona, M. Cragven, J. Ibbetson, P. Kozodoy, S. Keller, J.S. Speck ,U.K. Mishra

Materials and Electrical Engineering Departments
University of California Santa Barbara
Santa Barbara, CA 93106 USA

Lateral epitaxial overgrowth (LEO) of low defect density GaN on Si(111) and Sapphire substrates is demonstrated and characterized using scanning electron microscopy, atomic force microscopy, transmission electron microscopy, x-ray diffraction, photoluminescence spectroscopy, and cathodoluminescence imaging. Devices fabricated on LEO materials shown improved characteristics, in particular a large reduction in leakage current under reverse bias is observed for p-n junction and UV photodetectors. In recent work we have dramatically improved internal efficiency and threshold current for blue laser diodes. For laser diodes fabricated on LEO wing regions we have observed threshold current densities as low as 4.8kA/cm2 , which is much improved in comparison to 9kA/cm2 on conventional planar GaN/sapphire structures. For UV detectors fabricated on the "wing" region of the LEO a reverse-bias dark current of 10nA/cm2 is measured, in contrast to 300mA/cm2 for conventional dislocated GaN diodes. LEO diodes also exhibit a decrease in unwanted sub-band gap spectral response and improved signal-to-noise characteristics due to reduced dislocation densities.

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Crystalline and Optical Properties of ELO GaN Using W Mask by MOVPE and HVPE

K. Hiramatsu[1], H. Miyake[1], A. Motogaito[1], H. Sone[2], Y. Kawaguchi[2], N. Sawaki[2] Y. Iyechika[3] and T. Maeda[3]

[1]Dept. of Electrical and Electronic Engineering, Mie Univ., 1515 Kamihama, Tsu 514-8507, Japan
[2]Dept.of Electronics, Nagoya Univ., Furo, Chikusa, Nagoya, 464-8603, Japan
[3]Tsukuba Research Laboratory, Sumitomo Chemical Co., Ltd, 6 Kitahara, Tsukuba 300-3294, Japan
Tel/Fax: +81-59-231-9694, e-mail: hiramatu@elec.mie-u.ac.jp

GaN and related nitride semiconductors have attractive wide-band-gap semiconductors for optical or electronic device applications. Selective area growth (SAG) and epitaxial lateral overgrowth (ELO) are promising techniques via MOVPE or HVPE to obtain various 3D structures and high quality epitaxial layers with low dislocation density. It is important to investigate GaN structures precisely via MOVPE or HVPE for aiming at decreasing dislocation density further, improving device performance and understanding the growth mechanism. GaN structures using SAG and/or ELO have been controlled by mask size, mask direction, mask material, mask fill factor, growth temperature, flow rate of source, ambient gas, impurity, substrate and surface structure (such as PENDEO epitaxy). We will present recent results on ELO GaN on the metal mask of W compared with SiO_2 by MOVPE [1] and also HVPE [2, 3].

(1) SAG of GaN using W mask by MOVPE
We fabricated SAG structure of GaN using W mask by an atmospheric MOVPE system. The selectivity of GaN growth on the window regions was excellent. The structures of GaN on the $<11\bar{2}0>$ and $<1\bar{1}00>$ stripe pattern by SAG had the different shapes, the triangular structures with $\{1\bar{1}01\}$ facets are formed on the $<11\bar{2}0>$ stripe pattern and the trapezoidal structures with (0001) surface on the top and rough facets on the both sides are formed on the $<1\bar{1}00>$ stripe pattern. The growth mechanisms of the facet formation of GaN using W mask were similar to that using SiO_2 mask.

(2) ELO of GaN using W Mask by HVPE
The ELO of GaN with stripe W mask pattern is performed by HVPE and a buried structure of the W mask with a smooth surface is achieved for the stripe mask patterns of $<11\bar{2}0>$ and $<1\bar{1}00>$. Optical and crystalline characteristics of the ELO-GaN are investigated by means of CL image and x-ray rocking curve (XRCs). It is found that the CL intensity due to the near-band edge emission is stronger in the laterally overgrown region in comparison with that in the normal growth region. The ϕ-ω scan of XRCs reveals that the tilting of the c-axis is much smaller in the ELO-GaN grown with the W mask than that grown with a SiO_2 mask.

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Selective Area Epitaxial Growth of AlInGaN-GaN over Sapphire, SiC and Silicon Substrates

M. Asif Khan, J. W. Yang, G. Simin, X. Hu, and V. Adivarahan
Dept. ECE, University of South Carolina, Columbia SC 29208

R. Gaska and M. S. Shur
Rensselaer Polytechnic Institute, Troy, New York 12180-3590

and

J. E. Van Nostrand
WPAFB, Dayton, Ohio.

In this paper, we will report on selective area growth of GaN layers, AlGaN/InGaN Multiple Quantum Well structures, and AlInGaN-GaN heterojunctions using low pressure MOCVD on sapphire, SiC and silicon substrates. The selective area growth was carried out using PECVD deposited SiO_2 masking layers.

Using this approach, we fabricated GaN *npn* bipolar-junction-transistors with the emitter junction grown in a selective area over the p-type GaN over sapphire substrates. These devices used much improved Pd/Au p-contacts (R_c around 1×10^{-6} ohm-cm^2 at 250°C) and demonstrated gains as high as 20 at 300°C. With improved device geometries, we expect to further improve these results. Under reverse-bias, the selectively grown emitter-base or the collector-base pn-junctions also operated as visible-blind ultraviolet detectors.

We also deposited crack-free GaN-AlInGaN heterojunctions and multiple-quantum wells over (111) Si substrates using selective area growth. For this study, prior to the heterostructures, we deposited AlN (0.1 microns using MBE) followed by a 0.5 micron thick GaN (MOCVD) as the buffer layers. By adjusting growth temperature and pressure we could change the buffer layer conductivity over several orders of magnitude thereby obtaining structures with vertical conduction. The InGaN-GaN MQWs (over Si substrates) have strong emission in the purple-blue region with intensity levels similar to that for standard high-quality structures over sapphire substrates.

We will also report on selective area deposition of GaN-AlGaN HEMTs over insulating and conducting SiC substrates.

Raman Microscopy of LEO GaN

Frederick Long
Rutgers University, Department of Chemistry

We have used confocal Raman microscopy to investigate lateral epitaxially overgrown (LEO) GaN on sapphire substrates. The one-phonon Raman spectra are consistent with pyramidal growth of the GaN before coalescence has occurred. The position and asymmetric line shape of the A1 longitudinal optical (LO) phonon demonstrate that the LEO GaN is doped. The dopant is most likely Si from the SiN mask used to produce the LEO GaN. The carrier concentration is estimated to be 1x1017 cm-3. We have also used Raman microscopy to spatially resolve the yellow emission from different regions of the LEO GaN.

Violet InGaN-MQW/GaN/AlGaN Laser Diodes Grown on LEO GaN

Shuji Nakamura

Department of Research and Development, Nichia Chemical Industries, Ltd.,
491 Oka, Kaminaka, Anan, Tokushima 774-8601, Japan
Phone:+81-884-23-7787 Fax:+81-884-23-1802 e-mail: shuji@nichia.co.jp

Major developments in wide-gap III-V nitride semiconductors have recently led to the commercial production of high-powe uv/blue/green/amber/white light-emitting diodes and violet laser diodes (LDs) [1,2]. The lifetime of the InGaN multi-quantum-well (MQW)-structure LDs has been improved to more than 10,000 hours under RT-CW operation using epitaxially laterally overgrown GaN (ELOG) [3] as a substrate and AlGaN/GaN modulation-doped strained-layer superlattices (MD-SLSs) as cladding layers [2]. These LDs with a lifetime of more than 10,000 hours had a low output power of 2-5 mW at RT. For applications such as read/write laser light sources of digital versatile disks (DVDs), the fundamental transverse mode is indispensable, under a variable operating current, for collecting the laser light to a small spot. Also for the writing use of the LDs for the applications of DVDs and HDDs, high-power LDs with an output power of more than 30 mW are required. Here, high-power InGaN-based violet LDs are described.

Type III-V nitride films were grown using the two-flow metalorganic chemical vapor deposition (MOCVD) method, the details of which have been previously described [1]. First, epitaxially laterally overgrown GaN (ELOG) was performed to reduce a number of dislocations due to a large lattice mismatch between GaN and sapphire substrate [3,4]. After obtaining a 20-µm-thick ELOG substrate, the laser structure was grown. The details of the growth conditions and laser structures are described in other papers [1]. No stimulated emission was observed which corresponds to a threshold current density of 3.6 kA/cm^2. The threshold voltage was 4.2 V. At an output power of up to 40 mW, no kink was observed in the L-I curve because the transverse mode was stable at a fundamental transverse mode with a small ridge width of 2 µm. Emission spectra of the LDs were measured under RT-CW operation. At output powers of 3mW, 10 mW, 30 mW and 50 mW, single- and multi--mode emissions were observed at wavelengths of around 408.1, 408.2 nm, 408.7 nm and 409.1 nm, respectively, as shown in Fig.1. The lifetime test was performed at a constant output power of 30 mW and an ambient temperature of 60°C. Untill 400 hours of operation, a constant degradation was observed. These rapid progress of InGaN-based LDs demonstrates that these LDs could be used for many applications, such as DVDs, HDDs, laser printers, sensors and excitation light sources in the near future.

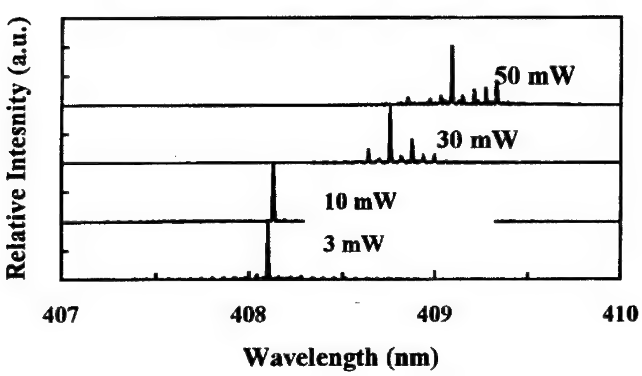

Fig.1. Emission spectra of InGaN-based violet LDs.

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Lateral Epitaxial Overgrowth for GaN-based LEDs

K. Jacobs*, W. Van der Stricht, I. Moerman, P. Demeester
University of Gent, Department of Information Technology – IMEC,
Sint-Pietersnieuwstraat 41, B-9000 Gent, Belgium
*Aspirant van het Fonds voor Wetenschappelijk Onderzoek (FWO) – Vlaanderen

E.J. Thrush
Thomas Swan & Co, Ltd., Button End, Harston, Cambridge, CB2 5NX, United Kingdom

GaN-based light emitting diodes (LEDs) were fabricated using laterally epitaxially overgrown (LEO) GaN substrate layers, grown by organometallic vapour phase epitaxy (OMVPE) on c-plane sapphire in a vertical rotating disk reactor. For comparison, the LED structures, with an InGaN/GaN multiple-quantum-well (MQW) as the active layer, were grown as well directly on top of (0001) sapphire as above ELOG layers.

Various characterisation techniques were applied to investigate the LEO layers, such as cross-sectional transmission electron microscopy (TEM), X-ray diffraction (XRD), photoluminescence (PL) and cathodoluminescence (CL). In accordance to other people's results, TEM indicated a substantial reduction of the threading dislocation density. Hence, optical and structural progress of the GaN material was obtained: PL revealed a decrease of the yellow luminescence, enhanced CL emission was collected from the overgrown regions, and finally XRD evidenced an improved crystalline quality by means of a reduction of the rocking curve FWHM by 20%.

The above mentioned improvement was reflected in an enhancement of the LEO LED performance, compared to conventionally grown LEDs. The leakage current under reverse bias conditions was observed to decrease, but also an increase of the output power by two orders of magnitude was discovered (*Figure 1*), as opposed to what other groups reported. This might indicate that in our case threading dislocations do act as efficient non-radiative recombination centers in the conventional LEDs on (0001) sapphire, with a carrier diffusion length, which is large enough for the carriers to be trapped by the dislocations, due to a shorter average distance between these defects.

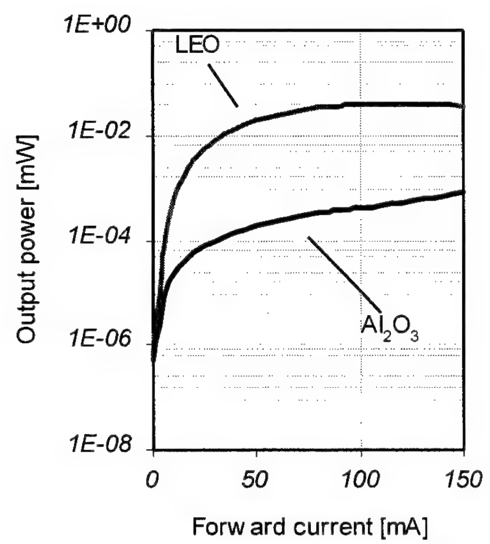

Figure 1 *– Output power LEDs on ELOG vs sapphire*

Recently, pendeo-epitaxy (PE), another selective area growth technique, has been introduced as an alternative for LEO, so eventually it would be interesting to know if a similar output power behavior is also retrieved in LEDs on pendeo-epitaxially grown GaN substrates. First results on PE on sapphire substrates indicated a further structural improvement, since in our case surface morphology and crystalline quality turned out to be better for the PE layers than for the ELOG films. X-ray diffraction was used to probe the material and the corresponding rocking curves showed FWHMs around 200 arcsec, which is a 30% reduction with respect to our ELOG results. PL characterisation gave rise to comparable enhancement of the optical quality.

* Electronic mail: koen.jacobs@intec.rug.ac.be. Tel. +32 9 264 3316

Nitride Materials Quality as a Key to Better Device Performance

M. S. Shur and R. Gaska
Electrical, Computer, and Systems Engineering and Center for Integrated Electronics and Electronics Manufacturing
Rensselaer Polytechnic Institute, Troy, NY 12180-3590
shurm@rpi.edu

M. A. Khan
Department of ECE, University of South Carolina, Columbia, SC 29208

Unique properties of nitride semiconductors make them superior for many applications. The maximum density of the two-dimensional electron gas at the GaN/AlGaN heterointerface or in GaN/AlGaN quantum well structures can exceed 2×10^{13} cm^{-2}, which is an order of magnitude higher than for traditional GaAs/AlGaAs heterostructures. The mobility-sheet carrier concentration product for GaN-based two-dimensional systems might also exceed that for GaAs/AlGaAs heterostructures and can be further enhanced by doping the conducting channels. We estimate that current densities over 20 A/mm can be reached in GaN-based Heterostructure Field Effect Transistors. These high current values can be combined with very high breakdown voltages. Recent Monte Carlo simulations point to strong ballistic and overshoot effects in GaN and related materials, which should be even more pronounced than in GaAs-based compounds but at much higher electric fields. Self-heating, which is unavoidable in power devices, raises operating temperatures of power devices well above the ambient temperature. For GaN-based devices, the use of SiC substrates having high thermal conductivity ensures effective heat dissipation. Such an approach combines the best features of both GaN and SiC technologies; and GaN/SiC-based semiconductors and heterostructures should find numerous applications in power electronics. Materials quality is the key to realizing a high potential of GaN-based materials system. Such factors as surface states, interface states at AlGaN/GaN heterointerface, dislocations, partially relaxed strain, surface roughness, surface polarization domains, and compensation all play a role in degrading device performance. This is evidenced by the 1/f noise studies, by the mobility dependence on temperature, Al mole fraction, and barrier thickness, and by the effects of the surface passivation on leakage currents.

Electronic Device Implications of LEO

Umesh Mishra
Electrical & Computer Engineering Department
University of California
Santa Barbara, CA 93106

Lateral Epitaxial Overgrowth (LEO) provides us the opportunity to eliminate dislocations and their attendant problems from device structures. This offers four very important advantages.

1. Improved electron mobility in HEMT structures
2. Low dislocation related trap densities and hence lower 1/f noise and phase noise in devices,
3. Low leakage currents in vertical devices such as bipolar transistors and solar blind photo-diodes, and
4. Improved junction placement for enhanced emitter injection effiicicency in HBT structures.

In this talk we will address the work done in all these areas at Santa Barbara and show that indeed leakage currents in HEMTs, p-n junction diodes and solar blind photodetectors were reduced by several orders of magnitude. However, no direct evidence of enhanced mobility was observed in the HEMTs. This may be due to enhanced scattering caused by point defects introduced to render the LEO material semi-insulating. Results on 1/f noise will also be presented.

LEO for AlGaN Electronic Devices: Do we need it?

J. C. Zolper
Office of Naval Research
800 North Quincy Street, Arlington, VA 22217-5660, USA
PH: 703-696-1437; Fax: 703-696-2611
zolperj@onr.navy.mil

AlGaN based HEMTs with dislocation densities of at least 1×10^{7} cm^{-2} (on SiC) have now demonstrated large signal microwave power densities up to 6.8 W/mm at 10 GHz. HEMTs with dislocations $\geq 1 \times 10^{8}$ cm^{-2} (on sapphire) have also achieved power densities over 4 W/mm at 6 GHz and power added efficiencies as high as 78 % at 4 GHz. The model of Weimann, et al., for the effect of dislocations on the transverse (perpendicular to the dislocations) mobility in GaN predicts a saturation in the mobility once the dislocation density approaches 1×10^{8} cm^{-2} for a channel sheet charge of 1×10^{13} cm^{-2}. If this is true, and in light of the impressive microwave results to date, it would appear that a further reduction in the dislocation density via lateral epitaxal overgrowth is unnecessary. In this talk I will outline other device issue that may warrant dislocation reduction such as improvements in thermal conductivity, reduction in carrier traps, and the long term reliability of high power devices. The potential role of dislocations in vertical power devices will also be raised.

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Dislocation Arrangements in Thick LEO GaN

S.E. Babcock,[1,3] K.A. Dunn,[1,3] D.S. Stone,[1,3] Ling Zhang[2] and T.F. Kuech[2,3]
[1]Materials Science and Engineering Dept., [2]Chemical Engineering Dept., and [3]Materials Science Program, University of Wisconsin, Madison, WI 53705

Diffraction-contrast transmission electron microscopy and micro-diffraction techniques were used to uncover and characterize dislocation arrangements a thick (15 mm), coalesced GaN film grown by MOVPE LEO. The windows in the LEO substrate were (1.5) mm wide with a 12 mm spacing and their long axis oriented along the <1$\bar{1}$00> direction of underlying GaN on sapphire. Trimethylgallium (TMGa) and ammonia precursors with a V/III ratio of 1800 were used to grow the film in 2 hours at 1100°C. Under these conditions, the cross-section of the growing GaN prior to coalescence is a beveled rectangle with side walls parallel {11$\bar{2}$0} and bevels on {11$\bar{2}$1}. As is commonly observed, the threading dislocations that are duplicated from the template above the window bend until they lie parallel to the substrate plane and are annihilated at the coalescence plane. The GaN that grows directly above the window has a lower dislocation density as a result. However, new, dense dislocation complexes that appear to originate from the coalescence plane are generated in the top half of the film. Dislocation loops appear to nucleate at the boundary and extend in a very reproducible pattern into the film a distance that is proportional to the distance of from the substrate. These dislocations first appear about 6 micron from the substrate, which is also the thickness by which almost all of the original threading dislocations have bent into the (0001) plane. Sets of loops sweep out an approximately triangular bar shaped volume centered on the plane of coalescence. The result is an increasingly higher dislocation density with distance from the substrate and a complex dislocation arrangement in the thick, coalesced GaN film.

This work is supported by the ONR MURI on Compliant Substrates at the University of Wisconsin (UW) - Madison. The NSF-MRSEC at UW provides partial support for the UW electron microscopy facilities.

High Temperature Masks for the Selective and Lateral Overgrowth of SiC and AlN

Christopher Thomas, Crawford Taylor, Ebenezer Eshen, and M.G. Spencer
Howard University Materials Science Center of Excellence
Washington DC. 20059

Lateral Epitaxial Overgrowth (LEO) has been successfully applied to several materials systems. Recently, this technique has had great results as applied to the growth of GaN. In this talk we will discuss the application of LEO and selective area techniques to the growth of Silicon Carbide (SiC) and Aluminum Nitride (AlN). These materials systems (particularly SiC) require the use of high temperature masking techniques. We have experimentally investigated the use of three different types of high temperature masks for the lateral overgrowth of SiC and AlN. These masks are graphtec mask (formed by carbonization of photoresist), oxidized AlN (formed by oxidation of MOCVD AlN) and oxidized tantalum (formed by the oxidation of evaporated Ta). These masks have been evaluated in a sublimation reactor and Chemical Vapor Deposition reactor (CVD) in the case of SiC and a Metal Organic Chemical Vapor Deposition (MOCVD) reactor in the case of AlN. In the case of SiC the graphtec mask techniques works well in the sublimation reactor at growth temperatures in excess of 1700 ^{0}C. When the graphetec mask is used in the CVD reactor there is the possibility of etching of the mask by hydrogen however in practice we have not observed this effect. Using the graphtec mask we have observed nucleation on the mask. At low temperature (aprox. 1300 ^{0}C) there is complete coverage of the graphtec mask with a poly SiC film. At temperatures of 1600 ^{0}C there is nucleation of a Si rich material, which is loosely bonded to the mask and can be removed by etching and physical agitation. Use of the oxidized Ta mask results in reduced nucleation in the sublimation reactor. Effect of these masks on the growth of AlN will be discussed.

Local Epitaxy and Lateral Epitaxial Overgrowth of SiC

Y. Khlebnikov, I. Khlebnikov, M. Parker, and T. S. Sudarshan

Department of Electrical and Computer Engineering
University of South Carolina
Swearingen Engineering Center
Columbia, SC 29208
sudarsha@engr.sc.edu <mailto:sudarshan@engr.sc.edu>

In this paper we report for the first time selective epitaxial growth and lateral epitaxial overgrowth of SiC using a graphite mask. The selective area SiC growth reported here is accomplished using physical vapor transport (PVT) epitaxy. The growth was carried out on 6H-and 4H-SiC wafers with on- and 8* off-oriented from the basal plane in the <<...>> direction. A graphite mask, consisting of rows and columns of uniformly-spaced open squares (50 mm x 50 mm) or circles (75 mm diameter) was used for the selective nucleation of SiC mesa structures. Using PVT epitaxy, selective area hexagonal-shaped structures were successfully grown. Essentially, there is no direct growth of SiC from the graphite film. A lateral/vertical growth rate ratio of 6 was achieved. Optical and scanning microscope images show perfectly-formed hexagonal islands, which are located over the open square or circular windows. High lateral resolution Raman spectroscopy will be used to investigate the structural (polytype, crystal order, etc.) and other electronic (e.g., carrier concentration) properties of these structures. The results suggest that the selective area epitaxial growth of SiC is a promising technique for obtaining a high quality of the locally-grown structures for SiC device applications.

The Selective Epitaxy of 3C-SiC on Si and 6H-SiC Substrates

J.H. Edgar, Department of Chemical Engineering, Durland Hall, Kansas State University, Manhattan, KS 66506-5102, e-mail: edgarjh@ksu.edu

The process parameters and materials involved in the selective deposition of 3C-SiC on silicon and 6H-SiC were examined. The deposition of SiC on carbonized Si(001) and Si(111) became highly selective over thermally grown silicon dioxide with the addition of HCl. The addition HCl reduced the SiC growthrate by a factor of 2.5 for a Cl/Si gas phase ratio of 40 compared to films deposited without HCl, and changed the film structure from polycrystalline to epitaxial. The best selectivity was achieved with a gas phase Cl/Si ratio exceeding 20 for films deposited at atmospheric pressure. Simultaneous Si etching during SiC deposition was observed. Increasing the temperature from 950 °C to 1000 °C increased the SiC growth rate by more than 30%, increased the crystal grain size, but accelerated the degradation of the silicon dioxide mask.

With increasing temperature, longer deposition times, and a thinner mask thickness, the SiO_2 mask failed by two mechanisms: delamination from the silicon substrate, and a roughening of mask surface. Delamination occurred primarily due to the formation of volatile silicon monoxide via the reaction $SiO_2 + Si = 2SO$ at the mask substrate interface. Into the gap created at the mask-substrate interface a thin SiC film would form, further accelerating the delamination. Top surface roughening of the mask occurred with the additional reaction between the carbon source, ethene, and the SiO_2. Thermal grown SiO_2 on 6H-SiC substrates also decomposed, albeit at a slower rate, presumably from reactions with the silane and ethene to form SiO and CO.

The properties of silicon nitride deposited by plasma-enhanced CVD as a mask were also evaluated. The silicon nitride appeared more durable, with no evidence of decomposition, but exhibited poorer adhesion, due to the large temperature change from the mask deposition temperature to the SiC deposition temperature. Further work is underway to evaluate the suitability of regular CVD silicon nitride as a mask.

Lateral Epitaxial Overgrowth of 3C-SiC on Silicon Substrates

S. E. Saddow,[1] G. Carter,[1] B. Geil,[2] T. Zheleva,[2] G. Melnychuck,[1] M. E. Okhuysen[1], M. S. Mazzola,[1] G. Katulka,[3] R. D. Vispute,[4] T. Venkatesan,,[4] M. Derenge,[2] M. H. Ervin,[2] and K. Jones[2]

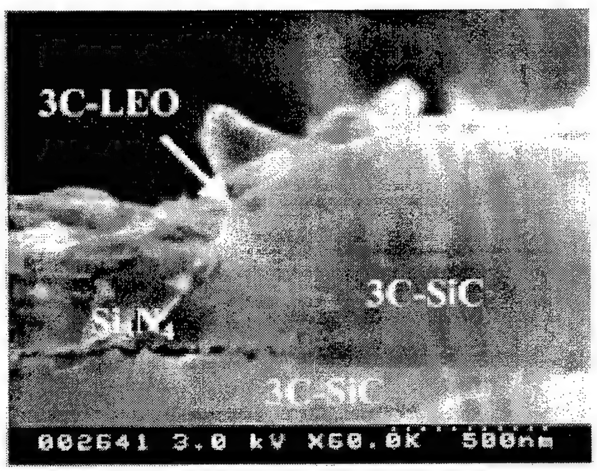
[1]Emerging Materials Research Laboratory, Department of Electrical & Computer Engineering, Mississippi State, MS 39762-9571, USA

[2]Sensors and Electron Devices Directorate, Army Research Laboratory, 2800 Powder Mill Road, Adelphi, MD 20783-1197, USA

[3]Weapons and Materials Research Directorate, Army Research Laboratory, Aberdeen Proving Ground, MD 21005-5066 USA

[4]Center for Superconductivity Research, University of Maryland, College Park, MD 20742 USA

LEO experiments have been performed on Si_3N_4 and AlN patterned 3C-SiC on Si substrates. 3C-SiC epi was grown at the Emerging Materials Research Laboratory on (100) Si substrates via CVD for 2 hours to deposit a 4 μm layer using a standard 3C-SiC growth process [1]. Si_3N_4, amorphous (deposited using PLD) and crystalline (deposited using MOCVD) AlN were then deposited on the 3C-SiC epitaxial layers with a thickness of 0.1, 0.1 and 0.16 μm, respectively. The dielectric films were then patterned at the Army Research Laboratory using a mask that contains 1 cm cells with varying stripe width, S, and window width, W, so as to experimentally determine the optimum geometry to achieve LEO of 3C-SiC on Si. Each cell contained W x S dimensions of 5x5 4x6, 3x7 and 2x8 μm, and were patterned using an ion milling tool. The samples were then subjected to a solvent clean and dried with N_2 prior to loading into the epi reactor. The growth then proceeded with the introduction of the H_2 carrier gas and SiH_4 and C_3H_8 precursor gases at a growth temperature of 1285 °C using a low-temperature 3C-SiC growth process developed in our laboratory [2]. In these initial experiments no steps were taken to prevent the nucleation of 3C-SiC on the Si_3N_4 or AlN masks To assess the vertical and lateral growth rates and assist in the assessment of the nucleation of 3C-SiC in the window regions, 10, 30 and 60 minute growth runs were executed with an estimated 3C-SiC film thickness of 0.17 and 0.34 and 0.68 μm, respectively. It was determined from these experiments that the optimum geometry was 5x5 and 6x4 μm, with 3C-SiC clearly nucleated in all of the window areas of each patterned region. SEM characterization was performed on the samples and it was initially believed that lateral growth had begun (see figure), with a trapezoidal growth profile as had been observed for GaN LEO [3]. However, TEM characterization indicated that even for the 10 minute growth run 3C-SiC was present on the dielectric stripes and we are currently investigating if lateral growth was achieved or if 3C-SiC nucleated directly on the dielectric mask. The latest results from this on-going research activity will be presented along with future plans.



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Investigation of the Nucleation of CdTe on Si Surfaces by TEM, XPS and RHEED

S. Sivananthan and R. Sporken
University of Illinois at Chicago, Microphysics Laboratory, Department of Physics (M/C 273)
845 W. Taylor St., Chicago, IL 60607-7059

During the past decade, MBE has evolved as an accurate and flexible manufacturing technology for HgCdTe, moving swiftly from a research technique onto the production line. Precise control, coupled with the capability to switch from one composition to another, large area growth on alternative substrates such as silicon (Si), and the growth of in-situ doped multilayers for simultaneous multicolor detection are some of the milestones of this technology that have led to HgCdTe becoming the material of choice for high-performance infrared focal plane arrays (IRFPAs). Our recent results on the selective area epitaxy have paved the way for monlithic IRFPA.

We have attained coherent growth of CdTe on Si, despite the 19.6% lattice mismatch between the film and substrate. Here, a clear understanding of the nucleation mechanism has paved the way to prepare the substrate surface in such a manner to form an interface where the lattice mismatch strain is almost completely relaxed by misfit dislocations.
A review of the CdTe/Si interface formation will be presented. Here we report on a study of nucleation and selective growth of CdTe on Si(111) by MBE. First, we compared growth of CdTe on Si(111) with and without first depositing a monolayer of As. Without the As monolayer, CdTe(111)A is obtained, with a very rough interface due to strong interaction between Te an Si at high temperature. On the other hand, the As monolayer favors growth of CdTe($\bar{1}\bar{1}\bar{1}$)B with a very sharp interface between CdTe and Si. XPS and energy dispersive spectroscopy show that the entire As monolayer remains at the interface. The ($\bar{1}\bar{1}\bar{1}$)B orientation is thought to be due to the formation of Cd-As bonds at the interface. A small number of Te-Si bonds is also detected by XPS and can be explained by Te atoms near steps or in vacancies in the As layer.

Recently, it has been found that lateral epitaxial overgrowth (LEO) can help reduce dislocation densities in layers grown on substrates with a large lattice mismatch [1]. This raises the question whether LEO can be used to reduce dislocation densities in CdTe grown on Si. For LEO to be possible, one must achieve both selective nucleation and growth, and a high ratio between lateral and vertical growth rate. The highest temperature where CdTe nucleates on such Si surfaces is typically in the range of 220-250°C. On a SiO_2 mask, CdTe nucleates at the same temperatures, leading to polycrystalline growth. Hence, SiO_2 is not suitable as a mask to achieve selective growth. Selective growth was achieved by exploiting the fact that homoepitaxy of CdTe is possible around 300°C, which is at least 50°C higher than the temperature required to nucleate CdTe on Si(111). First, a thin seed layer of CdTe was grown using our regular CdTe/Si(111) growth procedure. Two sets of CdTe stripes, parallel to $[01\bar{1}]$ and $[\bar{2}11]$, were defined by optical lithography, leaving areas of bare Si(111) between the stripes. CdTe was then grown by MBE on such patterned substrates, at a substrate temperature near 300°C. This results in growth on the stripes, and no growth between the stripes, as confirmed by SEM and scanning Auger microscopy.

Silicon-on-Sapphire

Isaac Lagnado
SPAWAR Systems Center San Diego
D805
San Diego, CA 92152

The early sixties were at the beginning of the electronics revolution where silicon integrated circuits built their current dominance, fundamentally and pervasively on tailor-made materials, starting at the atomic level. Thin-film deposition techniques, particularly chemical vapor deposition (CVD) and molecular-beam epitaxy (MBE) were developed to provide control over material constituents "in atomic amounts", in order to form the active part of high-performance devices. Nonetheless, the CVD techniques failed to provide a crystalline silicon structure amenable to advanced devices on insulating substrates, particularly sapphire.

In this presentation, the major issues, which confronted the formation of very thin layers of silicon (30-100 nm) on sapphire substrates for application to sub 100-nm device technology, will be reviewed. The focus of the investigation was, and still is, to achieve a structure in which the modern CMOS technology, the mainstay technology and workhorse of the electronic revolution, can be affordably implemented. In this context, one approach to the obtention of crystalline, device-quality thin film silicon-on-sapphire (TFSOS), namely the double Solid Phase Epitaxy (DSPE), has achieved truly outstanding results which are presently incorporated into high-performance products, such as phase-locked loop (PLL) ICs for wireless communication, and analog-to-digital converters for space application.

Besides the materials properties, devices' performances (f_t >100GHz) and circuits' applications (analog and mixed signals), present investigations aimed at producing stressed layers of $Si_{1-x}Ge_x$ (x>0.75) grown on TFSOS will also be described. Based on the present results, TFSOS could become entrenched, as CMOS, as new materials and devices appear – witness the recent success in developing highly-engineered structures with SiGe on TFSOS (hole mobility, through Hall measurements, is in excess of $800 cm^2/V.sec$) – using the established industrial infrastructure.

Scaling LEO to Large Area Growth

J. Ramer, M. Schurman and I. T. Ferguson
EMCORE Corporation, 394 Elizabeth Avenue, Somerset, NJ 08873

V. M. Asnin and F. H. Pollak
Physics Department, Brooklyn College, Brooklyn, NY 11210

L. Yue and G. S. Gargill
Lehigh University, Bethlehem, PA 18015

It is unlikely that large area (>2"), cost effective, bulk GaN substrates will be commercially available in the near future. It has been suggested that Lateral Epitaxial Overgrowth (LEO) will provide a source of 'virtual' substrates for III-Nitride growth. Using LEO it may be possible to develop large area (>3-6" diameter) and low defect ($<10^{5-6}$ cm^{-2}) GaN as a basis for electronic and optoelectronic devices. Much of the growth of III-Nitrides has taken place on 2" sapphire wafers and there is a need to drive growth to larger and cheaper substrates such as silicon to further enable the technology. The ability to grow GaN over large areas has been limited by a lack of a suitable growth technology and has been further complicated by a large difference in the CTE between the epilayer and substrate.

The current implementation of the LEO technology for III-Nitrides is an expensive, low yield, process requiring multiple growth runs and fabrication steps. This clearly makes the LEO process very expensive, negating any cost saving associated with using cheaper substrates and may limit its use to niche applications. In order to develop a cost effective, manufacturable, LEO process a one-step growth process is required in which a pre-patterned substrate grown on without the need for a GaN template.

Another major hurdle for large area GaN growth is the development of a suitable reactor technology. The key design issues for GaN MOCVD reactors are independent reactor size: 1.) Temperature control and uniformity over a wide range of growth temperatures (500–1100 °C). 2.) Stable and reproducible flow patterns over a wide range of pressures and temperatures. 3.) Alkyl/hydride separation for the control of pre-reactions. 4.) Robustness/lifetime of wafer carrier and heater subsystems. The most stringent requirement is for good temperature unformity over the wafer which will become even more critical as area increases.

A large difference exists in the coefficient of thermal expansion (CTE) between the III-Nitride epitaxial layer and the substrate. This thermal mismatch leads to the generation of defects in the GaN and cracking when the hetero-epitaxial layer and the substrate are cooled after growth. It is clear that the difference in CTEs and the generation of associated defects must be minimized.

This talk will focus on the issues that will have to be addressed to develop LEO as a robust, cost effective, manufacturable process. Spatially resolved thermal conductivity and cathodoluminesence measurements will also be reported. A clear increase in the thermal conductivity from 1.3 to 1.7-1.8 W/cm-K was observed for the LEO material corresponding to a reduction in defect density. A similar correlation between the yellow emission in the CL spectrum and defect density was also observed.

Recent Development in Nitride Emitters on SiC

H.S. Kong, and J. Edmond, G. Bulman, K. Doverspike, K. Haberern, D. Emerson, H. Dieringer, Cree Research, Inc, 4600 Silicon Drive, Durham NC 27703.

Y-K Song, M. Kuball and A. Nurmikko
Brown University, Providence RI 02912.

Blue light emitting diode (LED) and laser diode (LD) structures were fabricated by metal-organic chemical vapor deposition (MOCVD) from the AlN-InN-GaN system on single crystal 6H-SiC substrates. A conducting buffer layer was developed for these devices which uses an AlGaN buffer layer and provides a conduction path between SiC substrate and the active device region. Violet and blue multiple quantum well (MQW) separate confinement heterojunction (SCH) LDs were fabricated having InGaN wells and GaN barriers. High-quality cleaved facets are produced by wafer cleaving and facet coating is utilized to reduce threshold current values. Laser emission has been obtained for wavelengths from 393-434 nm. Threshold currents as low as 107 mA (15.7 V) have been obtained in 4-well 3 x 500 um lasers having 93%/99% reflectivity facet coatings. This corresponds to a current density of 7.1 kA/cm^2. Lasing has also been obtained in these same devices at duty cycles up to 75%. The work on lateral epitaxial overgrowth will also be presented.

DoD Basic Research and Interests in Wide Bandgap Semiconductors

R.J. Trew
Director of Research
ODUSD (S&T)
U.S. Department of Defense
Arlington, VA

The Department of Defense invests about $1.1B annually into basic research, with the majority of these funds supporting research performed at academic institutions. The basic research program is implemented through the Services' core programs and the University Research Initiative (URI), which is managed by the Research Office in the Office of the Deputy Under Secretary of Defense for Science and Technology. The URI includes a variety of programs such as the Multi-Disciplinary University Research Initiative (MURI), the Defense University Research Instrumentation Program (DURIP), the Presidential Early Career Awards in Science and Engineering (PECASE), and several other programs. These programs are executed through the Services' research offices, with management oversight by the DUSD(S&T) Research Office. The basic research program provides support for long term research in areas of interest for future military systems as described in the Basic Research Plan (BRP) published by Office of the Secretary of Defense.

In this presentation the structure and management of the DoD basic research program will be described. Emerging areas of focused support including national thrusts in information technology and nanotechnology will be described. Basic research focus areas, as defined under the DoD Strategic Research Areas (SRA's), will be presented and discussed. Emerging topic areas of interest in semiconductor materials and devices research will be discussed, with an emphasis upon wide bandgap semiconductors. There is a shift in emphasis in DoD support for long range materials and electronics research and support programs are becoming increasingly focused upon nanoscience and nanotechnology topics. Advances in understanding fundamental physics and engineering on the nanoscale are viewed as critical to development of next generation devices and systems. Progress in nanotechnology is enabled by remarkable success in semiconductor materials growth technology, nanoscale patterning resolution, and device fabrication technology. It is now possible to fabricate, literally atom-by-atom, semiconductor materials that do not exist in nature and with properties that are near ideal for application in electronic and optical applications. These materials are being used to fabricate devices that may have operational characteristics orders of magnitude beyond the capability of current devices. Electronic devices based upon the AlGaN/GaN system, in particular, have the potential for power performance an order of magnitude greater than traditional devices. This research is expected to provide the basis for next generation systems. DoD interests and related program support for work in these areas will be discussed.

Dr. Susan Babcock
Materials Science & Engineering
University of Wisconsin-Madison
1500 Engineering Drive
Madison, WI 53706
USA
Phone: 608/263-5696
Fax: 608/263-1087
E-mail: babcock@engr.wisc.edu

Dr. Bernard Beaumont
Centre de Recherche sur L'Heteroepitaxie et ses Applications
CRHEA-Cnrs
1 Rue Bernard Gregory
Sophia Antipolis
06560 Valbonne
FRANCE
Phone: + 33 4 93 95 42 27
Fax: + 33 4 93 95 78 28
E-mail: bb@crhea.cnrs.fr

Mr. Geoff Carter
Student
Mississippi State University
Dept. of Electrical & Computer Engineering
Box 9571
Mississippi State, MS 39762
USA
Phone: 601/325-2019
Fax: 601/325-2298
E-mail: gec1@ECE.MsState.EDU

Dr. Amir Dabiran
Assistant Professor
University of Minnesota
Department of Electrical & Computer Engineering
200 Union Street, SE
5-151 EE/CSci
Minneapolis, MN 55455
USA
Phone: 612/626-0095
Fax: 612/625-4583
E-mail: dabiran@ece.umn.edu

Dr. Daniel Dapkus
W.M. Keck Professor of Engineering
University of Southern California
Department of Electrical Engineering & Materials Science
504 Powell Hall
Los Angeles, CA 90089-0241
USA
Phone: 213/740-4339
Fax: 213/740-7797
E-mail: dapkus@mizar.usc.edu

Dr. Robert Davis
North Carolina State University
Materials Science & Engineering
Box 7907
Raleigh, NC 27695-7907
USA
Phone: 919/515-3272
Fax: 919/515-7724
E-mail: robert_davis@ncsu.edu

Dr. Steven DenBaars
University of California
Materials Department
Santa Barbara, CA 93106
USA
Phone: 805/893-8511
Fax: 805/893-8983
E-mail: denbaars@engineering.ucsb.edu

Dr. Nibir Dhar
U.S. Army Research Laboratory
AMSRL-SE-EI
2800 Powder Mill Road
Adelphi, MD 20783-1197
USA
E-mail: dhar@nvl.army.mil

Dr. Vladimir Dmitriev
President
TDI, Inc.
8660 Dakota Drive
Gaithersburg, MD 20877
USA
Phone: 301/208-8342
Fax: 301/208-8342
E-mail: vladimir@tdii.com

Dr. Russell Dupuis
Professor
The University of Texas at Austin
PRC/MER 1.606D-R9900
Microelectronics Research Center
Austin, TX 78712-1100
USA
Phone: 512/471-0537
Fax: 512/471-0957
E-mail: dupuis@mail.utexas.edu

Dr. James Edgar
Kansas State University
Department of Chemical Engineering
Durland Hall
Manhattan, KS 66506
USA
Phone: 785/532-4320
Fax: 785/532-7372
E-mail: edgarjh@ksu.edu

Dr. Ian Ferguson
EMCORE Corporation
Contract Research
394 Elizabeth Avenue
Somerset, NJ 08873
USA
Phone: 732/271-9090 Ext. 4114
Fax: 732/271-9686
E-mail: ianf@emcore.com

Dr. Jaime Freitas
Naval Research Laboratory
ESTU, Code 6877
4555 Overlook Ave., SW
Washington, DC 20375-5347
USA
Phone: 202/404-4536
Fax: 202/767-1165
E-mail: Freitas@bloch.nrl.navy.mil

Dr. Pierre Gibart
Director of Research
Centre de Recherche sur L'Heteroepitaxie et ses Applications
CRHEA-Cnrs
1 Rue Bernard Gregory
Sophia Antipolis
06560 Valbonne, FRANCE
Phone: + 33 4 93 95 42 27
Fax: + 33 4 93 95 78 28
E-mail: pg@crhea.cnrs.fr

Dr. Stephen Hersee
Professor of Electrical Engineering
Center for High Technology Materials
The University of New Mexico
1313 Goddard, SE
Albuquerque, NM 87106
USA
Phone: 505/272-7823
Fax: 505/272-7801
E-mail: shersee@chtm.unm.edu

Prof. Kazumasa Hiramatsu
Mie University
Electrical and Electronic Engineering
1515 Tsu
Mie 514-8507
JAPAN
Phone: +81-59-231-9694
Fax: +81-59-231-9394
E-mail: hiramatu@elec.mie-u.ac.jp

Mr. Koen Jacobs
University of Gent
Dept. of Information Technology
Sint Pietersnieuwstraat 41
B-9000 Gent
BELGIUM
Phone: + 32 9 264 3316
Fax: +32 9 264 3593
E-mail: koen.jacobs@intec.rug.ac.be

Dr. Stacia Keller
University of California, Santa Barbara
Electrical & Computer Engineering Department
Engineering I, Room 1115
Santa Barbara, CA 93106
USA
Phone: 805/893-8278
Fax: 805/893-8714
E-mail: stacia@ece.ucsb.edu

Dr. M. Asif Khan
University of South Carolina
Dept. of Electrical & Computer Engineering
Photonics & Microelectronics Lab
Columbia, SC 29208
USA
Phone: 803/777-7941
Fax: 803/777-2447
E-mail: asif@engr.sc.edu

Dr. Igor Khlebnikov
University of South Carolina
Electrical & Computer Engineering Dept.
Swearingen Engineering Center
Columbia, SC 29208
USA
Phone: 803/777-7302
Fax: 803/777-8045
E-mail: khlebnik@engr.sc.edu

Dr. Hua-shuang Kong
Cree Research, Inc.
4600 Silicon Drive
Durham, NC 27703
USA
Phone: 919/361-5709, Ext. 5352
Fax: 919/313-5454
E-mail: kong@cree.com

Dr. T. S. Kuan
Professor
State University of New York at Albany
Department of Physics
1400 Washington Avenue
Albany, NY 12222
USA
Phone: 518/442-4489
Fax: 518/442-4607
E-mail: kuan@cnsibm.albany.edu

Dr. Thomas Kuech
University of Wisconsin-Madison
Department of Chemical Engineering
1415 Engineering Drive
Madison, WI 53706-1691
USA
Phone: 608/263-2922
Fax: 608/265-4036
E-mail: kuech@engr.wisc.edu

Dr. Isaac Lagnado
Senior Staff Scientist
US Navy, SPAWAR Systems Center
Communication & Information Technology
D 805, B111
53475 Strothe Road
San Diego, CA 92152
USA
Phone: 619/553-2682
Fax: 619/553-2924
E-mail: lagnado@spawar.navy.mil

Dr. Zuzanna Liliental-Weber
Lawrence Berkeley Lab.
1 Cyclotron Road
Mail Stop 62/203
Berkeley, CA 94720
USA
Phone: 510/486-6276
Fax: 510486-4995
E-mail: z_liliental-weber@lbl.gov

Prof. Frederick Long
Rutgers University
Department of Chemistry
610 Taylor Road
Piscataway, NJ 08854
USA
Phone: 732/445-6359
Fax: 732/445-6359
E-mail: fhlong@rutchem.rutgers.edu

Dr. Hugues Marchand
University of California, Santa Barbara
Materials Department
Santa Barbara, CA 93106
USA
Phone: 805/893-8869
Fax: 805/893-3262
E-mail: marchand@engineering.ucsb.edu

Dr. Umesh Mishra
Workshop Chairman
University of California - Santa Barbara
Electrical & Computer Engineering Department
Room 5109, Engineering 1
Santa Barbara, CA 93106-9560
USA
Phone: 805/893-3586 or 2953
Fax: 805/893-8714
E-mail: mishra@ece.ucsb.edu

Dr. Rich Molnar
MIT
Lincoln Laboratory
Room E-124K
244 Wood Street
Lexington, MA 02420-9108
USA
Phone: 781/981-4482
Fax: 781/981-1867
E-mail: rmolnar@ll.mit.edu

Dr. Bo Monemar
Linkoping University
Dept. of Physics & Measurement Technology
Linkoping S-581 83
SWEDEN
Phone: +46 13-281765
Fax: + 46-13-142337
E-mail: bom@ifm.liu.se

Dr. Hadis Morkoc
Virginia Commonwealth University
Department of Electrical Engineering
PO Box 843072
Richmond, VA 23284-3072
USA
Phone: 804/828-0181
Fax: 804/828-4269
E-mail: hmorkoc@vcu.edu

Dr. Tom Myers
Associate Professor
West Virginia University
Physics Department
PO Box 6315
Morgantown, WV 26506
USA
Phone: 304/293-3422, Ext. 1469
Fax: 304/293-5732
E-mail: tmyers@wvu.edu

Dr. Shuji Nakamura
Nichia Chemical Industries, Ltd.
Research & Development Department
Oka, Kaminaka, Anan
Tokushima 774
JAPAN
Phone: + 81-884-23-7787
Fax: + 81-884-23-1802
E-mail: Shuji@nichia.co.jp

Dr. Manijeh Razeghi
Northwestern University
CQD/ECE
2225 N. Campus Drive
MLSB Room 4051
Evanston, IL 60208-3118
USA
Phone: 847/491-7251
Fax: 847/467-1817
E-mail: razeghi@ece.nwu.edu

Prof. Stephen Saddow
Mississippi State University
Dept. of Electrical & Computer Engineering
Box 9571
Mississippi State, MS 39762
USA
Phone: 601/325-2019
Fax: 601/325-2298
E-mail: saddow@ece.msstate.edu

Dr. Michael Shur
Rensselaer Polytechnic Institute
Electrical, Computer, & Systems Engineering and
Center for Integrated Electronics and Electronics
Manufacturing
110 8th Street, Room 9017, CII
Troy, NY 12180-3590
USA
Phone: 518/276-2201
Fax: 518/276-2990
E-mail: shurm@rpi.edu

Prof. S. Sivananthan
Director/Microphysics Lab.
University of Illinois at Chicago
Department of Physics
845 W. Taylor Street
Room 2236 SES
Chicago, IL 60607-7059
USA
Phone: 312/996-5092
Fax: 312/996-9016
E-mail: siva@uic.edu

Dr. Jim Speck
Associate Professor
University of California
Materials Department
Santa Barbara, CA 93106
USA
Phone: 805/893-8005
Fax: 805/893-8983
E-mail: speck@mrl.ucsb.edu

Dr. Michael Spencer
Howard University
School of Engineering, R1124
2300 6th Street, NW
Washington, DC 20017
USA
Phone: 202/806-6618
Fax: 202/806-5367
E-mail: spencer@msrce.howard.edu

Prof. Robert Sporken
University of Illinois at Chicago
Department of Physics
845 W. Taylor Street
Room 2236 SES
Chicago, IL 60607-7059
USA
Phone: 312/355-0199
Fax: 312/996-9016
E-mail: Sporken@uic.edu

Prof. Tangali Sudarshan
University of South Carolina
Electrical & Computer Engineering Dept.
Swearingen Engineering Center
Columbia, SC 29208
USA
Phone: 803/777-7302
Fax: 803/777-8045
E-mail: sudarsha@engr.sc.edu

Dr. Tadeusz Suski
Professor of Physics
UNIPRESS, High Pressure Research Center
Polish Academy of Sciences
ul. Sokolowska 29
01-142 Warsaw
POLAND
Phone: + 48 22 37 42 05
Fax: +48 22 632 4218
E-mail: tadek@iris.unipress.waw.pl

Dr. Robert Trew
Director of Research
US Department of Defense ODDRE(R)
4015 Wilson Blvd.
Suite 209
Arlington, VA 22203
USA
Phone: 703/696-0366
Fax: 703/696-0569
E-mail: trewrj@acq.osd.mil

Dr. Akira Usui
Optoelectronics and High Frequency Device
Research Labs.
NEC Corporation
34, Miyukigaoka
Tsukuba 305-8501
JAPAN
Phone: +81-298-50-1149
Fax: +81-298-50-1106
E-mail: usui@optd.cl.nec.co.jp

Dr. Gary Wicks
University of Rochester
The Institute of Optics
518 Wilmot Building
Rochester, NY 14627
USA
Phone: 716/275-4867
Fax: 716/244-4936
E-mail: wicks@optics.rochester.edu

Dr. Colin Wood
Office of Naval Research
Electronics Division
Code 312
800 N. Quincy Street, Bellstow Tower One
Arlington, VA 22217-5660
USA
Phone: 703/696-4218
Fax: 703/696-2611
E-mail: woodc@onr.navy.mil

Mr. Xingang Zhang
Graduate Student
University of Southern California
Dept. of EE-Electrophysics
University Park - SSC 505
920 West 37th Place
Los Angeles, CA 90089-0483
USA
Phone: 213/740-6018
Fax: 213/740-8684
E-mail: xzhang@scf.usc.edu

Dr. John Zolper
Program Officer
Office of Naval Research
Code 312
800 N. Quincy Street
Arlington, VA 22217
USA
Phone: 703-696-1437
Fax: 703-696-2611
E-mail: zolperj@onr.navy.mil

Dr. Tsvetanka Zheleva
NRC/NAS Research Associate
Army Research Lab
2800 Powder Mill Road
ATTN: AMSRL-SE-EM
Adelphi, MD 20783
USA
Phone: 301/394-5763
Fax: 301/394-2103
E-mail: Tsvetanka_Zheleva@ncsu.edu

TMS Workshop Planner:
Shari Allwood
Allwood & Associates, Inc.
8279 Midland Road
Mentor, OH 44060
Phone: 440/951-1380
Fax: 440/951-1381
E-mail: AllwoodInc@aol.com